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Decision support methodology for national energy planning in developing countries: An implementation focused approach

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Abstract

Energy is a crucial input to almost all economic activities, in addition to being necessary in supporting human development efforts. The energy planning (EP) activity is a principal step in the development of an energy strategy. EP objectives that are specific to the local context of the EP activity may aid in ensuring the implementability and sustainability of energy plans and policies.

The purpose of this research was to identify EP objectives specific to the local context of developing countries, together with their relative operational attributes, and to structure these within a transparent multi-objective decision making methodology for EP at the national level. A national energy system model was constructed to support this EP methodology. The countries of the Economic Community of West African States (ECOWAS) were used as a representative area of study.

The first stage of the work consisted of structuring the energy planning problem. A review of EP practices and methods currently in use in the ECOWAS was completed to identify gaps in the state of the art and to develop recommendations to guide the work. An EP methodology was established to allow for the EP activity to be conducted in a strategic, systematic, and transparent manner supporting all the actors involved. Context specific EP objectives were identified and made operational with quantifiable attributes, in addition to a set of commonly considered EP objectives.

The second stage comprised the development of a national energy demand and supply system model for application in a case study country: Ghana. A baseline energy demand and supply projection was developed. Additionally, a set of EP alternatives was established representing future energy policy pathways.

The third stage of the work was the development of a multi criteria decision aid (MCDA) methodology for use in the evaluation of EP alternatives in achievement of the EP objectives.

The fourth stage consisted of a case study conducted for the ECOWAS member state of Ghana. The case study was conducted to implement the national EP methodology in a real world application and to assess the outcomes of the use of the context specific EP objectives.

The work proposed and applied a methodology for EP at the national level in developing countries consisting of the three main activities of problem structuring, energy modeling and MCDA evaluation. The proposed methodology provides a procedure for the development of EP objectives specific to the context of application and the transparent systematic analysis of a set of EP alternatives, to support energy policy development.

Resumo

A energia tem um contributo crucial em praticamente todas as atividades económicas, além de ser necessária para o desenvolvimento civilizacional em sentido geral. A atividade do planeamento energético (PE) tem um papel importante no desenvolvimento de estratégias energéticas. Os objetivos do PE, que são específicos do seu contexto local de atividade, podem contribuir para assegurar a viabilidade e sustentabilidade das políticas energéticas.

Esta investigação teve como propósito identificar os objetivos do PE, específicos do contexto local dos países em desenvolvimento, em conjunto com os seus respetivos atributos operacionais, estruturando-os dentro de uma metodologia transparente de apoio à decisão multi-objectivo para o PE a nível nacional. Foi construído um modelo de sistema energético nacional para suportar esta metodologia. Os países da Comunidade Económica dos Estados da África Ocidental (CEDEAO) foram usados como área de estudo representativa.

A primeira etapa do trabalho consistiu em estruturar a problema do PE. Foi concluída uma revisão das práticas e métodos de PE, usados atualmente no CEDEAO, para identificar lacunas no estado da arte e formular recomendações para orientar o trabalho. Foi estabelecida uma metodologia de PE para permitir o desenrolar da sua atividade de uma forma estratégica, sistemática, e transparente para apoiar todos os fatores envolvidos. Foram identificados os objetivos do PE, específicos do contexto local, e foram operacionalizados com atributos quantificáveis, além de um conjunto de objetivos de PE geralmente considerados.

A segunda etapa incluiu o desenvolvimento de um modelo de oferta e de procura de energia para o sistema energético nacional, destinado ao país em estudo, o Gana. Foi desenvolvido um cenário de referência para a evolução futura de oferta e de procura de energia. Adicionalmente foi estabelecido um conjunto de alternativas de PE que descrevem percursos de futuras políticas energéticas.

A terceira etapa do trabalho consistiu no desenvolvimento de uma metodologia multicritério de apoio à decisão (MCDA) para ser utilizada na avaliação das alternativas que irão permitir a realização dos objetivos do PE.

A quarta etapa é constituída pelo estudo de caso realizado para o Gana, um estado membro do CEDEAO. Este estudo teve como objetivo a aplicação da metodologia do PE nacional num contexto real e a avaliação dos resultados da aplicação dos objetivos de PE específicos deste contexto.

O trabalho propôs e aplicou uma metodologia para o PE ao nível nacional dos países em desenvolvimento, que consistiu nas três atividades principais da estruturação do problema, modelação energética e avaliação MCDA. A metodologia proposta apresenta uma estrutura para o desenvolvimento dos objetivos específicos do contexto da aplicação e a avaliação sistemática e transparente de um conjunto de alternativas de PE, para apoiar o desenvolvimento das políticas energéticas.

Contents

Abbreviations

AC	Air-conditioning
AHP	Analytical Hierarchical Process
b/d	Barrels per day (petroleum)
bbd	Barrels (petroleum)
BP	British Petroleum
CaVE	Cabo Verde Modelo Energético
CEDEAO	Comunidade Económica dos Estados da África Ocidental
CCGT	Combined Cycle Gas Turbine
CDU	Crude oil distillation unit
CFL	Compact fluorescent lamp
COMAP	Comprehensive Mitigation Analysis Process
CoreUrban	Urban core
CRT	Cathode ray tube
DC	Decision conference
DEFENDUS	Development-Focused END-Use oriented Service-directed
DEP	Decentralized energy planning
DM	Decision maker
DSM	Demand Side Management
EC	Energy Commission of Ghana
ECG	Electricity Company of Ghana
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EDI	Energy Development Index
EER	Energy efficiency ratio
EFOM	Energy Flow Optimisation Model
EI	Energy intensity
ELECTRE	ELimination Et Choix Traduisant la REalité (ELimination & Choice Expressing REality)
ENS	Energy not supplied
EP	Energy planning
EPRAP	Energy for Poverty Reduction Action Plan
ES	Energy security
FE(C)	Final energy (carrier)
FEI	Final Energy intensity
GAMS	General Algebraic Modeling System
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Graphical information systems
GNI	Gross national income
GPRS	Ghana Poverty Reduction Strategy
GridCo	Ghana Grid Company
GRIP	Generalized Regression with Intensities of Preference
GT	Gas Turbine
GVA	Gross value added
H2RES	Energy planning of islands and isolated regions
HDI	Human Development Index
HHS	Households
HVAC	Heating ventilation and air-conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRP	Integrated Resource Planning
JSMAA	Java implementation of SMAA methods (software)
KAMM	Karlsruhe Atmospheric Mesoscale Model
KITE	Kumasi Institute of Technology, Energy and Environment
KNUST	Kwame Nkrumah University of Science and Technology (Ghana)
LCD	Liquid crystal display
LEAP	Long-range Energy Alternative Planning
LED	Light-emitting diode
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADM	Multi-attribute decision making
MAED	Model for Analysis of Energy Demand
MARKAL	MARKet ALlocation
MAUT	Multi-attribute utility theory
MAVT	Multi-attribute value theory
MCDA	Multi-criteria decision assessment (or analysis or aid)
MDG	Millennium Development Goal (United Nations)
MESSAGE	Model of Energy Supply Systems and their General Environmental Impacts
MESTI	Ministry of Environment Science Technology and Innovation (Ghana)
MMSCFD	Million standard cubic feet per day
MODM	Multi-objective decision making

MoE	Ministry of Energy (Ghana)
MoP	Ministry of Power (Ghana)
NEAP	National Energy Efficiency Action Plan
NEB	National energy balance
NEB	National Energy Board (Ghana)
NED	Northern Electricity Department (Ghana)
NEMS	National Energy Modeling Systems
NES	National Electrification Scheme (Ghana)
NFI	National Focal Institute
NGC	Net generation capacity
NPA	National Petroleum Authority (Ghana)
OECD	Organisation for Economic Co-operation and Development
OLED	Organic light-emitting diode
OR	Operational research
OSeMOSYS	Open Source Energy Modelling System
PAIRS	Preference Assessment By Imprecise Ratio Statements
PE(S)	Primary energy (supply)
PE	Planeamento energético (Used only in the *Resumo*)
PeriUrban	Urban periphery
pkm	Passenger kilometer (mobility)
POLES	Prospective Outlook on Long-term Energy Systems
PROMETHE	Preference Ranking Organization METHod for Enrichment of Evaluations
PSM	Problem structuring methods
PURC	Public Utilities and Regulatory Commission (Ghana)
PV	Photo voltaic
PVSyst	Photovoltaic System Studies
RAC	Reliably available capacity
RETSCREEN	Renewable-energy and Energy-efficient Technologies Clean Energy Project Analysis Software
RFCC	Residual fuel catalytic cracker
RFO	Refined fuel oil
RIEP	Regional Integrated Energy Plan
RMGC	Remaining margin of generation capacity
SAIDI	System average interruption index
SAPP	Sunon Asogli Power Plant
SE4ALL	United Nations Sustainable Energy for all Initiative
SEA	Strategic environmental assessment
SHEP	Self-Help Electrification Program
SIMPACTS	Simplified Approach for Estimating Impacts
SMAA	Stochastic Multi-Criteria Acceptability Analysis
SMART	Specific, Measurable, Achievable, Realistic and Timed
SNEP	Strategic National Energy Plan (Ghana)
SODA	Strategic Options Development and Analysis
SPLAT-W	System Planning Tool (West African Power Pool system)
SSA	sub-Saharan Africa
SSM	Soft Systems Methodology
SWOT	Strengths, Weaknesses, Opportunities and Threats
TAPCO	Takoradi Power Company
TDL	Transmission and distribution system losses
TEC	The Energy Center (KNUST, Ghana)
TICO	Takoradi International Company
TIMES	The Integrated MARKAL-EFOM System
tkm	Ton kilometer (mobility)
TO	Tullow Oil
TOR	Tema Oil Refinery
TRL	Technology Readiness Level
UN	United Nations
UNCTAD	UN Conference on Trade and Development
UNDP	UN Development Programme
UNEP	UN Environment Programme
UNFCCC	UN Framework Convention on Climate Change
UNIDO	UN Industrial Development Organization
US $	Dollars – United States of America
US EIA	Energy Information Agency - United States of America
VIP Analysis	Variable Interdependent Parameters Analysis
VISA	Visual Interactive Sensitivity Analysis
VOC	Volatile organic compound
VALCO	Volta Aluminum Company (Ghana)
VRA	Volta River Authority (Ghana)
WADE	World Alliance for Decentralized Energy
WAGP	West African Gas Pipeline
WAPCo	West African Gas Pipeline Company
WAPP	West African Power Pool
WASP	Wien Automatic System Planning Package
WAsP	Wind Atlas Analysis and Application Program
WINPRE	Workbench for INteractive PREference Programming
WISDOM	Woodfuel Integrated Supply/Demand Overview Mapping model

Symbols

$Access_{p,i}$ Share of households of population type *p* that have access to carrier *i* [%]

$Access_{1,y}$ Share of households with access to electricity in year *y* following the traditional method for evaluation (*1*) [%]

$Access_{2,y}$ Constructed value evaluating access, with the FE service method for evaluation (*2*) [constructed scale 0-12]

$Adequacy_y$ Adequacy of electricity generation in year *y* [-]

$Annual\ Generation\ capacity_{electricity,y}^{elec\ gen}$ Domestic electricity generation, FE carrier *i*, capacity in year *y* [ktoe]

$A_{p,i,y}$ Share of HHS of population type *p* that has access to carrier *i* in year *y* [%]

$Availability_g^{elec\ gen}$ Availability factor of electricity generation technology *g* [%]

c_r Correction factor for PE resource *r*, calculated as the share of PE resource *r* provided by indigenous sources. An increased indigenous PE supply of resource r results in an increased value for D_2 [-]

$Cap_{u,g,y}^{elec\ gen}$ Installed capacity of unit *u=1,2,3…,Y*, of generation technology *g=1,2,3,…W*, in year y [MW]

$\mathrm{Cap}_{g,y}^{elec\ gen}$ Total installed capacity of technology type *g* in year *y* [MW]

$capita_y$ Population in year *y* [people]

$Connect\ Cost_c$ Cost per new connection of type *c* [monetary units/ household]

$Connections_{p,c}$ Number of households newly connected in year *y* [households]

$Cost_{h,y}$ Total cost from sectors : h=1 →electricity generation capacity, h=2 → transmission and distribution system, & h=3 → New connections (access) & h=4 → petroleum refineries, in year *y* [US dollars]

D_1 Shannon-Weiner diversity index [-]

D_2 Shannon-Weiner diversity index, import reflective. [-]

$emission\ factor_{f,r}$ Default emission factor for emissions of GHG *f*, for fuel type *r* [kg/TJ]

ESA_1 Measure of diversity of PE supply [-]

ESA_2 Measure of diversity and import dependency of PE supply [-]

$\mathrm{ESA}_{\mathrm{import}}$ Import reflective measure of PE diversity [-]

$FEC_{petroleum}^{TOR}$ Petroleum based FE carrier outputs from the TOR for FE carrier *i* in year *y* [ktoe]

$FEI_{i,s,y}^{Ser}$ Final energy intensity at the energy service level for carrier *i* and service *s* in year *y* [ktoe/monetary units]

$FEI_{k,i,s,y}^{Sector}$ Final energy intensity at the energy service level for carrier *i* service *s* and year *y* for the

	Sector [ktoe/ monetary units] or [ktoe/pkm or tkm]
$FEI_{p,i,s,y}^{Res,\ app}$	The FE intensity per unit of appliance (e.g. appliance or technology) for population type *y* for FE carrier *i* attributable to FE service *s,* in year y [ktoe/appliance]
$FEI_{p,i,s,y}$	Final energy intensity for population type *p* for final energy carrier *i* and final energy service *s,* in year *y* [ktoe/household]
$Fuel\ cost_g$	Cost of fuel that corresponds to technology *g* [monetary units /ktoe]
g=1,2,3,…W	Newly installed electricity capacity types [-]
g_{ij}	Performance element i of alternative a_i corresponding to the attribute j.
$GHG_{f,d,y}$	Total emissions of GHG *f=1…N* from emission source sector, d=1 – electricity generation (stationary), d=2 petroleum refining (stationary) and d=3 transportation [kton/year]
$GHG_{f,y}$	The total emissions of GHG *f,* for GHG *f*=1…N, in year *y* [kton]
GVA_y^{Sector}	Gross value added by the S*ector* in the year *y* [monetary units]
$Growth\ _b$	Growth rate of line type *b* where b=1 is transmission and b= 2 is distribution [km/year]
GWP_f	Global Warming Potential of GHG *f* [-]
$HHS_{p,y}$	Households of population type *p* in year *y* [households]
i=1,2,3,…M	Final energy carrier types [-]
int	The fixed annual interest rate [%]
$inv.\ cost_b$	Unit investment cost of line (transmission and distribution) type b [monetary units /km]
$\mathrm{inv.\ cost}_g$	Unit investment cost for technology type *g* [US dollars /kW]
$Investment_{intervention}$	Cost for installed capacity for each specific *intervention* considered [monetary units]
k=(k_1…k_n)	Importance parameters in the linear additive value function.
$Local\ Env.\ Impact_y$	Local environmental impact in year *y* [constructed scale 0-3]
$Loss_y^{dist}$	Effective losses resulting from the distribution system in year *y* [%]
$Loss_y^{trans}$	Effective losses resulting from the transmission system in year *y* [%]
L_u^E	Evaluated level of local environmental impact (*E*) of the generation technology type. [constructed scale 0-3]
L_u^M	The evaluated level of maintainability (*M*) of installed generation technology type *u* [constructed scale 0-3]
m_r	Share of net import in PE supply of resource *r [%]*
$Maintainability_y$	Maintainability of the of the electricity generation system in year *y* [constructed scale 0-3]
$Mobility_{k,i,q,y}$	The mobility for subsector *k* and FE carrier *i* for either passenger (q=1) or freight (q=2) in year *y* [ktoe/ (pass or tkm)]
$Mobility_{s,y}$	Mobility in the sector for the year *y* for subsector *s*, for passenger [ktoe/pkm] and freight [ktoe/tkm]
N	Loan's term in number of years (or number of yearly payments) [years]
NGC_y	The net installed generation capacity in the given year [MW]

$Oper.\&Maint.cost_{b}$	The operation and maintenance cost as a share of the total value of existing stock [%]
$Oper.\&Maint._{g}$	Annual unit operation and maintenance costs for installed capacity [monetary units /kW]
$Own_{p,i,s,y}$	Level of ownership of units at the household level for population type y for FE carrier i attributable to FE service *s*, in year y [appliance/household]
p_r	Share that primary energy resource *r* in total primary energy supply, for all resources in r=1…U: (U primary energy resources used) [%]
p_{loan}	Loan amount or the loan's principal. This is calculated by the difference of the total investment cost and the initial down payment. [monetary units]
p=1,2,3	Residential population type 1→ CoreUrban, 2→PerUrban, & 3→Rural [-]
$PES_{r,g}$	PES requirements of resource *r* for electricity generation unit *g* [ktoe]
$PES_{DST,y}$	PES requirements of direct solar thermal energy (DST),in year *y* [ktoe]
$PES_{r,d,y}$	Primary energy supply combusted for electricity generation (d=1) or petroleum refining (d=2) of fuel type *r* [ktoe]
$PES^{TOR}_{crude\ oil,y}$	PES requirements for the TOR of crude oil, in year *y* [ktoe]
$PES^{Imp}_{crude\ oil,y}$	PES imports of crude oil in year *y* [ktoe]
$PES^{Imp}_{petroleum,y}$	Imported PES for petroleum products, in year *y* [ktoe]
$PES^{Imp}_{natural\ gas,y}$	PES imports of natural gas in year *y* [ktoe]
$PES_{natural\ gas,g,y}$	PES requirements of natural gas for electricity generation unit *g*, in year *y* [ktoe]
$PES^{Imp}_{coal,y}$	PES imports of coal, in year *y* [ktoe]
$PES_{coal,g,y}$	PES requirements of *coal*, for electricity generation unit *g*, in year *y* [ktoe]
$PES^{Imp}_{imported\ electricity,y}$	The imported electricity, in the year *y* [ktoe]
$PES_{biomass,y}$	Total PES requirement of biomass, in year *y* [ktoe]
$PES^{charcoal}_{biomass,y}$	Biomass PES requirement for production of charcoal, in year *y* [ktoe]
$PES^{M\ elec\ gen}_{r,y}$	PES requirement, *r*, for electricity generation for minigrids (M) in year, *y* [ktoe]
$PES^{S\ elec\ gen}_{r,y}$	PES requirement, *r*, for electricity generation for standalone systems (S) in year, *y* [ktoe]
$PES^{elec\ gen}_{r,y}$	PES requirement, *r*, for electricity generation in year, *y* [ktoe]
$Production\ capacity^{TOR}_{i,y}$	The annual production capacities for each output FE carrier *i* and year *y*. [ktoe]
$Q_{charcoal,y}$	FE Demand in year *y* for charcoal [ktoe]
$Q^{M\ total}_{electricity,y}$	Total FE demand for minigrid (*M*) supplied electricity, in year *y* [ktoe]
$Q^{S\ total}_{electricity,y}$	Total FE demand for minigrid (*S*) supplied electricity, in year *y* [ktoe]
$Q^{Sector}_{i,y}$	Aggregate FE demand for FE carrier *i* in year *y* for FE demand *Sector* [ktoe]
$Q^{Sector}_{i,s,y}$	Aggregate FE demand for FE carrier *i* in year *y* for, FE service *s*, in FE demand *Sector* [ktoe]

$Q^{Sector}_{k,i,s,y}$	FE demand for FE carrier i attributable to FE service *s* in subsector *k* in year y for the *Sector* [ktoe]
$Q^{total}_{DST,y}$	FE demand for *the DST FE carrier*, in year *y* [ktoe]
$Q^{total}_{i,y}$	Total FE demand for FE carrier *i* in corresponding year *y* [ktoe]
$Q^{total}_{electricity,y}$	Total FE demand for electricity in year *y* [ktoe]
$Q^{total+TDL}_{electricity,y}$	Total FE demand for electricity, with transmission and distribution system losses (TDL) in year *y* [ktoe]
$Q^{total}_{fuelwood,y}$	Total FE demand for fuelwood in year *y* [ktoe]
Q^{TOR}_{i}	Final energy demand for FE carrier *i* supplied by the oil refinery [ktoe]
$Q_{k,i,y}$	FE demand from sector *k* for FE carrier *i* in year *y* [ktoe]
$Q^{Res}_{p,i,s,y}$	FE demand from population type *p* for FE carrier i attributable to FE service *s*, in year y [ktoe]
r=1,2,3,…U	Primary energy resource types [-]
RAC_y	The remaining generation capacity that results from the difference of the NGC and the unavailable capacity in year *y* [MW]
$RMGC_y$	Remaining margin of electricity generation capacity in year *y* [MW]
$Rep^{j,\ app}_{i,s,y}$:	Representative efficiency of the end-use technology mix for the FE service *s* – carrier *i* combination in year *y*, calculated at for each sector *j* [%]
$Rep^{j,\ app}_{p,i,s,y}$	Representative efficiency of the end-use technology mix for the FE service *s* – carrier *i* combination in year *y*, calculated at for each sector *j*, and population type *p* [%]
s=1,2,3,…P	Final energy services considered [-]
$Share_{1,p,y}$	Percentage of households of population type *p* in year *y* that are assumed to have access, following evaluation method *1* [%]
$Share_{2,p,m,y}$	Percentage of households in population type *p* with access to portfolio *m* in year *y*, following evaluation method *2* [%]
$Share_c$	Share of new connections met by connection type *c* [%]
$Share_{f,y}$	Share that technology *f* represents in the transformation process in year *y* [%]
$share_{g,y}$	Share that technology *g* represents in the total installed capacity in year *y* [%]
$Share^{M\ elec\ gen}_{g,y}$	Share that technology *g* represents in the minigrid generation mix in year *y* [ktoe]
$Share^{elec\ gen}_{g,y}$	Share that technology *g* represents in the national mix (installed capacity) in year *y* [ktoe]
$Share_{k,i,y}$	Share that FE demand for carrier *i* represents in subsector *k* in the year *y* [%]
$Share_{k,s,i,y}$	Share that FE service *s* represents of FE demand for carrier i in subsector *k* in the year *y* [%]
$Share_{s,i,y}$	Share that FE service *s* represents of FE demand for carrier *i*, and year *y* [%]
$Share^{\ j,k}_{z,i,s,y}$	Share that technology z represents in the mix of appliances, z=1, 2, 3, ..., H, that provide FE service s for the respective carrier i in sector j and subsector k , in year y[%]
$Share^{\ j}_{z,i,s,y}$	Share that technology z represents in the mix of appliances, z=1, 2, 3, ..., H, that provide FE service *s* for the respective carrier *i* in the sector *j* and year *y* [%].

$Services_m$	FE services assumed available to households with access to portfolio *m* [count of FE services]
$Stock_{b,y-1}$	Total stock in distance of line type b in year *y-1* [km]
$Total\ Cost_y$	Total costs from all sectors considered, h=1 → electricity generation capacity, h=2 → transmission and distribution system, & h=3 → New connections (access) & h=4 → petroleum refineries in year *y* [Monetary units]
$Total\ GHG_y$	Total GHG emissions in year *y* [kton]
u=1,2,3…,Y	Electricity generation installed units [-]
u_j	Partial value function for the attribute j.
$unavailable\ capacity_y$	Generation capacity that is unavailable in year *y* calculated with the availability factor of each generation capacity technology type [MW]
$unit\ conversion_r$	Factors to convert units for result in calculation of GHG emissions [kg/kton & ktoe/TJ]
$V(a_i,k)$	Scored value for alternative j, for the set of importance parameters.
$value\ of\ stock$	Total value of existing stock, compounded from base year, [monetary units]
$w_{u,y}$	Share that the technology represented in the total installed capacity of electricity generation technologies in year *y* for all installed capacity generation technologies u=1, 2, 3, …,Y, in year *y* [%]
z=1,2,3,…N	End use technology appliances [-]
$\beta_{i,s,y}^{CU/PU}$	Ratio of FE demand for carrier *i,* and service *s,* attributable to Core Urban (CU) and PeriUrban (PU) populations in year *y* [-]
$\beta_{i,s,y}^{CU/R}$	Ratio of FE demand for carrier *i,* and service *s,* attributable to CoreUrban(CU) and Rural (R) populations in year y [%]
η^{DST}	Efficiency of PE to FE transformation of DST energy, in this case $\eta^{DST} = 100$ [%]
$\eta_f^{charcoal}$	Transformation efficiency in biomass to charcoal production of technology *f* [%]
η_g	Efficiency of electricity generation technology g [%]
$\eta_g^{M\ elec\ gen}$	Efficiency of minigrid electricity generation technology *g=1,2,3…,W* [ktoe]
$\eta_g^{S\ elec\ gen}$	Efficiency of standalone electricity generation technology *g* [ktoe]
$\eta_g^{elec\ gen}$	Efficiency of electricity generation technology *g* [ktoe]
$\eta^{refinery}$	The efficiency of the oil refinery [%]
$\eta_{z,i,s}^{end}$	The end-use efficiency of appliance type *z*, energy carrier *i,* and FE service *s* in sector *j* and subsector *k* [%]
$\omega_{i,s}$	Contribution to GVA of carrier *i* in the service *s* [%]
$\omega_{k,i,s}$	Contribution to GVA of the sector for subsector *k,* carrier *i* and service *s* [%]
$\Delta \mathrm{Mobility}_y$	The percentage change in mobility levels from the base year until year *y* [%]

Chapter 1

Introduction

1.1 Motivation

1.1.1 Role of Energy in development

Energy is essential to both the economic and human dimensions of development. It is a vital input to almost all economic activities. It also is necessary to support human development in meeting basic human needs for food and shelter. The provision of modern energy carriers to populations has numerous benefits including improved health, wellbeing and income-generating opportunities, as well as enabling access to employment, education, and social services (UN-Energy, 2007). The relationships, however, between energy and development are extremely complex, and energy is indispensable but not sufficient alone in bringing about the conditions for development (IEA, 2004).

A relationship exists between energy and economic growth as evidenced by Figure 1-1 representing economic activity as a function of electricity consumption (Stern, 2011). A general trend is seen in which countries with larger economic activity show higher energy consumptions. It is important, however, that energy is not viewed as the only ingredient to development, as no equation exists to calculate the energy requirements for a country simply given the GDP or vice-versa, and future economic developments and energy demand are often volatile (van Beeck, 2003).

Increased energy use does not necessarily coincide with increases in economic activity. The causal relationship in this energy consumption-growth nexus, has been the topic of extensive debate with no consensus on the direction of causality (Belke et al., 2010).

A decoupling of resource use, namely energy, and economic activity has been seen in developed countries especially following the first oil crises in the period from 1973 to 1985 (de Bruyn and Opschoor, 1997; Goldemberg et al., 1987; IEA, 2012a; Kander, 2002). This decoupling of economic growth is seen in the continued rise of GDP in OECD countries, in Figure 1-2 from 1971 until present, and the slower rate of growth for the energy inputs that prior to the 1980s grew at a rate corresponding to that of economic growth (Stern, 2011).

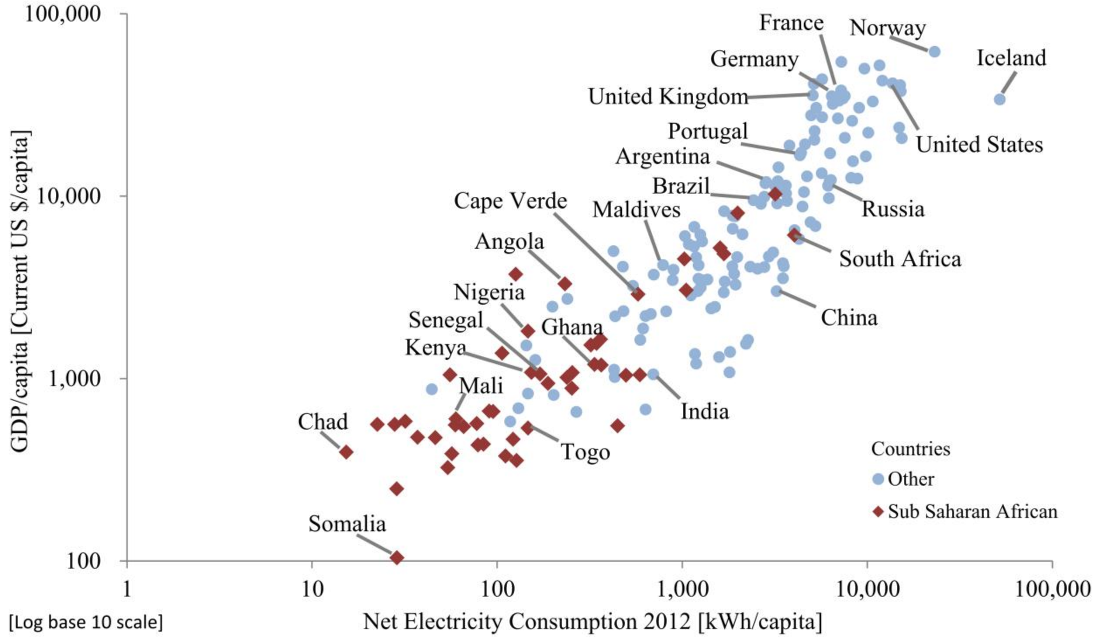

Figure 1-1 - Electricity consumption and GDP/capita (UN, 2014a, 2013; US EIA, 2015a)

The decoupling of energy consumption and economic activity is often explained through four factors (Stern, 2011). The first factor is whether energy and other inputs (e.g. capital) are substitutes or are complements. Here two inputs are said to be substitutes if the quantity of one (e.g. energy) increases when the price of the other (e.g. capital increases). This is opposed to complements in which an increase in the price of one input results in a decrease of the other input (Apostolakis, 1990). Industries may respond to changes in energy prices by alternating between different production techniques that use different input ratios (Stern, 2004). The second factor is innovation and energy efficiency, also referred to as *technology changes,* that allows for the use of less energy to produce the same amount of energy services resulting in reduced energy demand. An example of this second factor is an increase in energy efficiency due to government standards and labelling efforts, that encourage a shift to (or development of) efficient appliances. Third are shifts in energy quality and the composition of energy inputs that allow for a reduction in the amount of energy required to produce a unit of output. Energy quality is defined in this sense as the economic usefulness per heat equivalent unit. Some higher quality fuels are more flexible than others meaning that they can be transformed into a larger number of carriers or provide for more final energy (FE) services that also have outputs with higher economic values (Grubler, 1999; Smil, 2005; Stern, 2011). An example of a shift in energy quality is the move from fuelwood to electricity - a higher quality FE carrier, supporting more activities and possibly more valuable activities.

Additionally, a shift from coal to higher quality crude oil as a primary energy (PE) input may result in reduced energy intensity (EI). Finally, the fourth factor, structural changes, or shifts in the composition of outputs from an economy affect both GDP and energy consumption. A common example is that of countries whose economies, in the early stages of development, shift from agriculture towards industry and manufacturing that are more resource intensive and extractive, typically representing increased energy demand. In the later stages of development a shift occurs away from industry towards light manufacturing and services that are less resource intensive at the national level and represent a decreased energy use per unit output (Bhattacharyya, 2011; Stern, 2011).

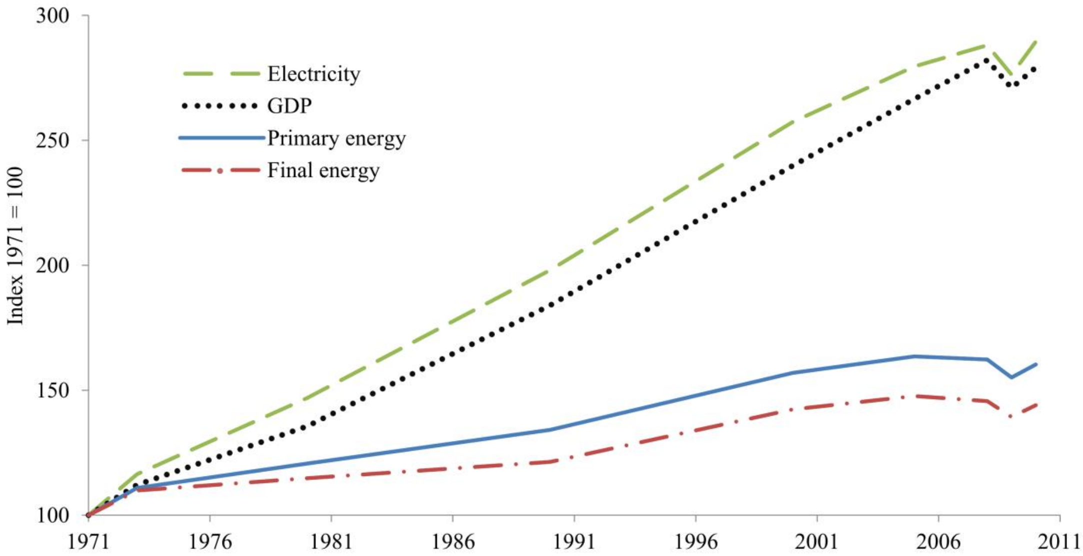

Figure 1-2 – GDP, PE supply, FE consumption and electricity consumption OECD countries (IEA, 2012a).

This decoupling of energy and economic activity has been observed in OECD countries that are at arguably higher stages of development than the majority of non-OECD developing countries. Despite this decoupling seen in countries at higher stages of development, small increases in energy consumption within developing countries can result in significant increases in quality of life (e.g. development of human welfare and economic growth) (IEA, 2004; REN21, 2005).

The energy sectors and the power sector in particular, in many developing countries are not adequately developed to support these economic and human developments, be it in terms of energy access levels, installed capacity, or overall levels of energy consumption (Castellano et al., 2015).

Increased access to modern energy has been linked to increased economic activity. This relationship of energy access and economic activity is seen in Figure 1-3 where nations that have rates of access to electricity of less than 80% show consistently lower GDP/capita than states with higher access rates (Castellano et al., 2015).[1] The measure of access to electricity gives a clearer indication of the level of energy poverty in a country than does the average consumption. In countries where a small portion of the population is responsible for the majority of the electricity consumption and the largest portion of the population consumes a marginal amount, the average can lead to an unclear indication of energy poverty.

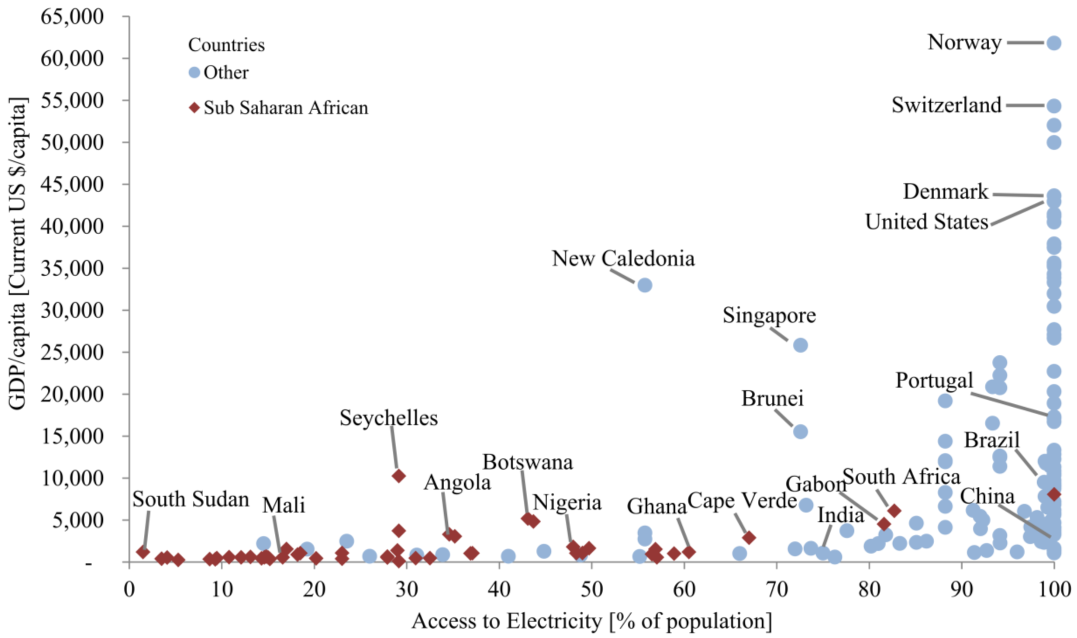

Figure 1-3 - Electricity access and GDP/capita (UN, 2014a, 2013; World Bank, 2015a)

Efforts have also shown the relationships that exist between access to modern energy carriers and human development and welfare. One such relationship is seen between the Energy Development Index (EDI) from the International Energy Agency (IEA) and the Human Development Index (HDI) from the United Nations Development Programme (UNDP). The EDI is a composite indicator of energy development at the national level, and provides a measure of a country's progress in transitioning to modern energy (IEA, 2012b).[2] The HDI was developed

[1] The outliers in this figure represent small nation states (e.g. Brunei) with significant natural resources or island nation states. The Sub-Saharan Africa states with a GDP/capita of approximately $5,000/capita represent states in the region with significant natural resources (e.g. Angola, Botswana, Gabon, and South Africa) or small island states (e.g. Seychelles, Cape Verde and Mauritius).

[2] The EDI indicator measures access at the household level with dimensions of both access to electricity and per capita residential consumption of electricity. At the household level a measure of the share of modern fuels within the residential sector final energy consumption is also included. At the community level the indicator measures per-capita public sector electricity consumption as well as share of productive uses in total FE consumption.

in an effort to assess country development levels through dimensions beyond economic growth by including considerations of human development (UNDP, 2015a).[3]

The EDI and HDI indicators provide information at the national level as to the level of access to modern energy carriers and the level of human development respectively. Increases in a country's progress in transitioning to modern energy are seen to correspond to increases in human development in Figure 1-4. The countries of sub-Saharan Africa (SSA) represent the majority of the countries with HDIs below 0.6. Small improvements in the EDI for countries below this level are seen to support rapid increases in the dimensions of human development as represented by the HDI. The improvements in HDI are seen to diminish with higher values of EDI.

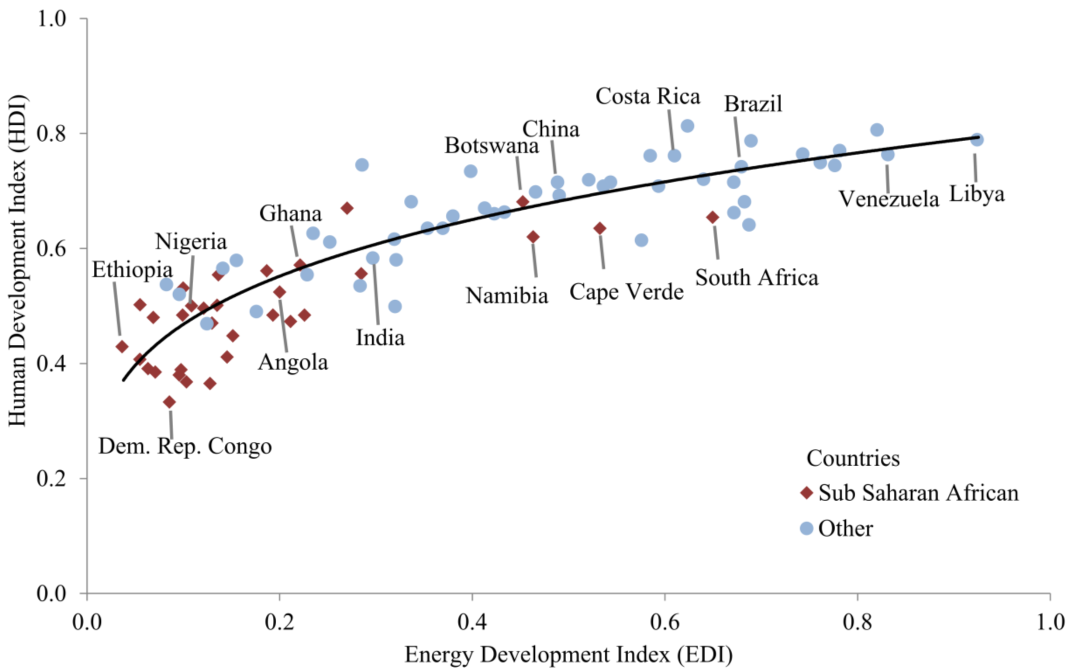

Figure 1-4 – Energy Development Index and the Human Development Index for select countries

The relationship between access to modern energy and human development seen in Figure 1-4 is more evident when the actual linkages between energy and human welfare are examined.

The United Nations Millennium Development Goals (MDGs) set eight specific objectives for human welfare development worldwide. These goals integrate social, economic and environmental linkages to human development in all of its dimensions (UN, 2014b). While access to modern energy services was not explicitly referred to in the MDGs, it has been

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[3] The HDI is a composite measure of achievement in the dimensions of life expectancy, education and gross national income per capita. The HDI is calculated as the geometric mean of indicators from these three dimensions.

recognized as an essential factor for their achievement. Modern energy access has been indirectly and directly linked to the successful achievement of the majority of the MDGs (DFID, 2002; REN21, 2005; UN-Energy, 2004; World Bank and UNDP, 2005).

Modern energy access is essential to efforts to overcome extreme poverty and hunger (MDG 1). Access to clean efficient modern energy carriers impacts the share of household income spent on cooking, lighting, and heating. Access to modern energy is an indispensable factor in the generation of employment, industrial activities, transportation, commercial services, and agricultural outputs (UN-Energy, 2004). Lighting allows for income generation activities to extend beyond daylight hours. Machinery provides for increased productivity in the productive sectors. Energy supports irrigation and post-harvest preservation (e.g. drying, cooling or freezing) activities that allow for increased food production and access to nutrition (DFID, 2002).

Energy access supports goals for universal primary education (MDG 2). Electric lighting in education facilities and housing accommodations aids in retaining teachers in rural areas and allows students to study beyond daylight hours. Electricity also supports the use of educational equipment (e.g. projectors and computers) (DFID, 2002). Children are often unable to attend school due to the essential chores of collecting fuelwood and water, and access to modern energy aids in removing this time pressure allowing for children study (UNDP, 2005; World Bank and UNDP, 2005).

Promotion of gender equality and women's empowerment have also been linked to energy access (MDG 3). The energy services used by men and women differ in relation to the economic and social division of labor both, in the workplace and at home, and so the genders are affected differently when access to modern energy is achieved. Women spend a disproportionate amount of time daily gathering fuelwood, collecting water, and completing household chores without modern appliances. This time could be shifted to income producing or educational activities with the provision of modern energy access (Misana and Karlsson, 2001; World Bank and UNDP, 2005).

Public health and modern energy access are closely linked (MDG 4, 5 and 6). The impact of indoor air pollution on morbidity and premature deaths of women and children is an important public health issue within many developing countries (World Bank and UNDP, 2005). Women and children are disproportionately affected by the indoor air pollution caused by cooking on traditional stoves with solid cooking fuels in poorly ventilated spaces. The supply of clean grid based water, modern energy, and adequate cooking spaces is a factor that can potentially greatly reduce child mortality rates (van der Klaauw and Wang, 2003).

Health facilities require reliable illumination, refrigeration, and sterilization equipment, in addition to media equipment that aids medical services in remote areas. Effective health services play a role in stopping the incidence of major diseases, improving women's mortality rates at birth, and aiding in medical emergencies, and they are inextricably linked to modern energy services (World Bank and UNDP, 2005).

Communication mediums such as radio, television and mobile phones are essential in the sharing of public health information and specifically in the combat of fatal diseases (Aranda, 2015; BBC News, 2014; World Bank and UNDP, 2005).

The extraction, refinement, transportation, transformation and use of energy impact the environment on the local, national and global scale (MDG 7). This includes indoor air pollution, emission of air and water pollutants from electricity generation, land degradation from fuelwood gathering, and finally global impacts on climate from emissions of greenhouse gases (GHGs) (World Bank and UNDP, 2005).

Modern energy access is therefore an essential component for both economic and human development. However, ensuring that populations have adequate access to modern energy in order to support this development presents an energy planning (EP) problem that must be addressed by the relevant actors involved, with methodologies that are adequate to the context.

1.1.2 The national energy planning problem

EP is essential to the development of an energy trajectory that supports economic and human development. The EP activity is the process of designing a future energy framework at the local, regional, multi-national, or global energy scale (WADE et al., 2009). It is an effort to balance the energy demand and supply forecasted for a population over a specific time horizon (Kahen, 1998). EP consists of selecting the PE sources, transformation technologies, FE carriers and, demand side management (DSM) efforts required for energy generation, transmission, and distribution to meet society's demand for FE services and fulfill national objectives.

The EP activity allows for the modeling of national demand and supply within possible future scenarios and the construction and comparison of multiple policy alternatives against, preferably, a "business as usual" future. The outputs from this process support governments in the development of policies or strategies to balance energy demand and supply while possibly also achieving objectives of economic development, environmental protection, energy security, or others.

Depending on the context, the energy system can be defined in a variety of ways. In general the energy system consists of an interconnected network of mechanisms that have the end goal of supplying society with the necessary energy services (Løken, 2007a). The system consists of all the technologies and activities required for the extraction and treatment of PE resources, the PE supply (PES), possible energy imports & exports, FE conversion technologies, required transmission and distribution systems, FE end-use conversion technologies, the energy services provided, as well as the losses that result. The boundaries of the system vary depending on the application. As an example, global EP consists of considerations from the conglomerate of all national energy systems and their interconnections. Local EP in some communities may include considerations of FE energy but does not necessarily include PE considerations.

Interests in EP and energy policy development are rooted in the increased dependence of industrialized countries on fossil fuels that occurred in the 20th century. These interests peaked with disruptions in the PES due to the oil crises of the 1970s. These events encouraged governments to think more proactively about the security of their energy supply in a strategic way.

The traditional EP activity, carried out prior to the crises of the 1970s was historically entrusted to the national governments as the sole provider of commercial energy (i.e. state owned electrical utilities) working to some level with private firms (World Bank, 1993). The goal of traditional EP was to forecast demand and establish supply options according to economic and financial objectives. Demand was forecast in an aggregated form with no explicit acknowledgement of the energy services that this demand represented. The future energy system, therefore, became an extrapolation of energy demand trends and the rigid fitting of an energy supply system (de Oliveira and Girod, 1990). The EP activity was concentrated on supply-side configurations, mostly ignoring, possibly more economically viable and or environmentally attractive, demand side alternatives. Energy conservation and substitution of FE carriers was absent from EP (World Bank, 1993).

Following the oil crises, fossil fuel supplies were no longer considered guaranteed. This fact motivated countries to make structural changes in energy systems and planning efforts. This included diversification of PE supplies beyond oil as well as the incorporation of non-fossil fuel resources in the PES. It also influenced the start of end-use EP efforts with the realization of the energy services provided by energy, identification of possible substitutions of energy carriers within these energy services, and increases in energy efficiency. This end-use approach was radically different from the traditional approach. With the end-uses planning approach, energy was not the end product for society, and more complex energy demand considerations could be brought into the scope of EP. Lighting, heating, transport, etc. were the energy services demanded by society and in turn the appropriate factors to forecast demand (de Oliveira and Girod, 1990).

Interests in EP and energy policy development also shifted from the narrow focus on energy security, of the traditional approach, to a broader vision that also includes economic, environmental and additional concerns (Logan and James, 2009).

With worldwide efforts towards liberalization of the energy sector, the sovereignty over EP that the state historically had changed as new actors have entered the scene bringing a diverse set of concerns to the EP activity. According to Catrinu (2006) these actors include companies involved in energy supply, municipal or regional administrative authorities, regulatory authorities, political groups, industrial and private energy consumers, environmental and other interest groups (e.g. NGOs and technology vendors). These actors consist of decision makers (DMs) and stakeholders that should be included in the EP activity (Webler and Tuler, 2006).

There have been increasing concerns about the implications of energy use on the global climate and the long term influences expected from the continued use of fossil fuels. There are also concerns about the relationship between security of PES and the large capacity expansions required globally, as well as the environmental ramifications that these changes will have in developed and developing countries.

As a result of these concerns, and the diverse set of actors, there has been a recent heightened interest in EP at all levels of government from the international and national down to the local municipal level (Covenant of Mayors, 2010; ECREEE, 2013a; European parliament, 2006). Energy and its importance within the framework to stem global climate change have influenced international EP efforts (Bruckner et al., 2014). At the regional level multi-national concerns are seen in the European Union (EU) with the Climate Action and Energy Package (Commission of the European communities, 2008). National interests have been seen in the EU with the development of the Energy End Use Efficiency and Energy Services Directive in addition to National Energy Efficiency Action Plans (European parliament, 2006). Activities are also present at the local municipality level (Covenant of Mayors, 2010).

How can EP objectives be best achieved, among the many future possible pathways, while ensuring that a society's demand for FE services are met, in addition to addressing the concerns of the multiple stakeholders involved? This is the EP problem that must be addressed by the actors involved in the development of energy plans and policies at all levels (e.g. national, local, etc.).

1.1.3 Energy planning concerns in developing countries

Developing countries are poised to emerge into the international market. The economy of SSA has doubled since 2000, reaching $2.7 trillion dollars in 2013. This output, from the 940 million inhabitants of the continent, is not comparable with the $3.2 trillion dollars of the German economy that has a population of 82 million (IEA, 2014a).[4] Continued economic growth will require access to reliable supplies of energy, and the governments of countries of SSA, as in other developing countries, will have to overcome multiple deficiencies in their

[4] 2013 US dollars- Purchasing parity terms [PPP].

energy systems in order to assure secure energy supply and efficient use of energy on the demand side (Castellano et al., 2015).

The countries of SSA present a broad representation of the energy and development challenges faced by developing countries. Angelou et al. (2013) identified 20 developing countries that accounted for more than two-thirds of the total population in developing countries without access to electricity. Of these 20 countries, 12 were in SSA. Also identified in the work were 20 countries that accounted for four-fifths of the total population of developing countries without access to modern energy cooking services. Of these 20 countries, 9 were located in SSA.

Approximately 1.28 billion people in the world, 18% the world's population, remain without access to electricity. This share increases to 58% on the continent of Africa and 68% of the population of SSA (IEA, 2014b).

Energy access concerns are not exclusive to electricity, but also for modern energy carriers. One indicator of access to modern energy is the share of population that relies on traditional use of biomass for cooking. According to this measure, approximately 38% of the population worldwide is without access to modern energy. This percentage increases to 67% for developing countries on the continent of Africa and reaches 80% of the population when concentrating on SSA (IEA, 2014c). Modern energy services including electric lighting, gas cooking, etc., customary in the everyday lives of populations in much of the developed world remain inaccessible for approximately 59% of the population of developing countries and 83% of the population of SSA (UNDP and WHO, 2009).[5,6]

It is evident in Figure 1-1 that the countries of SSA have rates of electricity consumption per capita well below those of developed countries such as the United States, France, or Germany. The residential population of 791 million in SSA, excluding South Africa, has an

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[5] Modern energy refers to carriers such as electricity, liquid fuels such as kerosene, gaseous fuels such as natural gas or LPG, and does not include traditional biomass and coal (World Bank and UNDP, 2005). Access to modern energy services refers to the services which modern energy allows such as cooking with LPG or pumping with electric pumps. Modern energy carrier often refers to commercial carriers such as gas and electricity. This definition is at the household level, and of course it leaves out productive purposes such as services, industry and transport which can also benefit from modern energy carriers.

[6] Definitions for developed and developing countries vary depending on the classification needs of the organization. The World Bank classifies according to Gross National Income (GNI) per capita. Low- to middle- income countries are considered developing and have GNIs/cap. of $1,045 and $12,746 or less respectively (World Bank, 2015b). The International Monetary Fund (IMF) uses the terms emerging and developing countries, a classification based on per capita income, export diversification, and degree of integration into the world financial system (IMF, 2015a; Nielsen, 2011). The United Nations refers to developing countries below the 75th percentile in the Human Development Index (HDI) distribution. The HDI is a composite index considering GNI, life-expectancy at birth, and measures of actual and expected years of schooling (UNDP, 2015a). Distinction is often made between members and non-members of the Organization for Economic Co-Operation and Development (OECD). Refer to Nielsen (2011) for a further discussion of definitions and evaluation methods.

aggregate annual electricity consumption comparable to that of the 19.5 million inhabitants of the state of New York with approximately 40 TWh annually. This results in electricity consumption rates per capita of approximately 51 kWh/capita and 2,051 kWh/capita for SSA and the state of New York respectively (IEA, 2010a).[7] In 2012 the total aggregate demand for electrical energy was approximately 352 TWh in SSA. This was only 70% of the total demand of South Korea, a developed country, which has only 5% of the population of SSA.

Despite the levels of total installed electricity capacity, the energy available to populations is significantly less than that which should be technically available. Insufficient, unreliable and inaccessible main grid electricity supply has led to a large dependence of fossil-fuel powered generators and a focus on standalone and mini-grid based electricity supply solutions (IEA, 2014a).

The total installed grid electricity generation capacity in SSA was 90 GW in 2012, of which roughly half is located in South Africa. Of total installed capacity in SSA, up to 25% was unavailable for reasons including lack of maintenance (Eberhard A. et al., 2008). This value reached 40% of unavailable capacity in Nigeria in 2012 (Castellano et al., 2015). On average for the SSA region, power is unavailable to consumers 540 hours annually or 6% of the year.

One principal reason for the lack of available capacity is that EP activities and ad-hoc measures in developing countries often entail the import and use of foreign technologies. This frequently leads to subsequent abandonment of the technology or project due to unforeseen barriers including but not limited to lack of local maintenance facilities, lack of local technical experts, unavailability of parts, and cost of maintenance and repair (Dunmade, 2002).

Large shares of the electricity generated do not reach consumers due to large transmission and distribution losses in the region that are greater than 20% for some countries. The average losses are 18% without including the country of South Africa (EC, 2006a; IEA, 2014a).

The current practice of “load shedding” or blackouts to prevent larger collapses of the national electricity grids have affected economies and life in the region (Onishi, 2015). The productivity of businesses in developing countries is greatly affected by the supply of reliable FE. At the local level a lack of reliable electricity supply results in the use of back-up generators fueled by diesel or gasoline fuels to ensure provision of energy. 47% of businesses in Kenya, as an example, own back-up generators (World Bank, 2013a). These redundant systems are an additional cost for households and businesses alike with fuel costs in 2012 in SSA estimated to have surpassed $5 billion.

[7] This electricity consumption per capita increases to approximately 400kWh/capita when only considering population with access, however this rate has remained relatively unchanged for the last decade as population has increased together with consumption levels (IEA, 2014a).

Accounting for the total electricity provided by back-up generators, approximately 16 TWh in the region results in a total electricity demand that is 3% larger than that recorded for grid demand (IEA, 2014a).

Interests in EP in developing countries have recently grown as in developed countries. They have been stimulated, however by the understanding that the provision of modern energy services is not just a luxury, but a developmental concern and essential for economic as well as human development efforts (ECREEE, 2013a; GNESD, 2009).

There has been a realization not only of the importance of EP but also the importance of the State's role in EP. This is due in part to the State's role in lending legitimacy to the EP activity and its responsibility to ensure affordable modern energy access to its citizens, something that may not necessarily be a key concern of private firms, which may, for example, not have profitable motivation in providing energy to rural areas (Club-ER, 2010; Siyambalapitiya, 2002).

In light of prevailing low energy access rates and the positive role that energy access plays in international development efforts, developing countries, economic communities, and international aid organizations alike have recently set ambitious targets for increased access to modern energies (Brew-Hammond, 2010; CEMAC, 2006; NEPAD, 2001; UNDP and WHO, 2009).

The United Nations Sustainable Energy for all Initiative (SE4All) has proposed the target of universal access to modern energy services by 2030 (AGECC, 2010). The Economic Community of West African States (ECOWAS) has targets of 100% access to modern cooking fuels, 60% access to energy for productive purposes, and 66% access to individual electricity supplies by the year 2015 (UEMOA and ECOWAS, 2006). ECOWAS countries, under the recent Energy Efficiency Policy and Renewable Energy Policy, will be obligated to develop national action plans and measures in response to regional energy targets set for 2030 (ECREEE, 2013a).

Overcoming the energy system deficiencies described and reaching these ambitious energy sector goals will require innovative energy policy frameworks supported by EP efforts.

Prior to the oil crises, as in developed countries, the traditional EP method in developing countries was a supply oriented activity focused on urban populations. The main goal of the EP activities was to supply modern energy to meet urban demand. Access would then be extended to satisfy rural demand (de Oliveira and Girod, 1990).

The dichotomy between urban and rural areas was further exacerbated following the oil crises as developing countries faced two simultaneous energy transitions. The urban areas of developing countries that had previously begun a transition to oil as a PE resource and modern energy carriers, began to transition to non-oil energy resources and increased energy efficiency. At the same time in rural areas where traditional energy resources, such as fuelwood, had still remained dominant, there was an emphasis in transitioning to oil as an energy resource and modern energy carriers.

Energy policy objectives similar to those in developed countries were adopted to address these energy transitions, and de Oliveira and Girod (1990) argued that many developing countries employed EP methods from more developed countries. They however were not always directly applicable. This was not due to inherent flaws in these methods, but rather due to the different objectives and nature of the EP activity in developing countries.

The EP activity in all countries is aimed at improving energy policy development, and de Oliveira and Girod (1990) argued that specific features exist in developing countries that greatly change the nature of the activity. The first feature is the lack of capacity to provide society with many basic needs including energy. For this reason, an analysis of the existing demand and supply of modern energy may not be fruitful, and EP efforts must transform possibly suppressed energy demand into effective energy demand. Secondly, populations are not heterogeneous and inequalities, such as income, are stark. This has implications in the representations of demand patterns for FE services and FE carriers. Thirdly, the energy systems in developing countries are nascent, and projects undertaken in these emerging energy systems may have characteristics beyond the traditionally analyzed economic cost-benefit analysis. Finally, the state continues to play a dominant role in the energy system of many developing countries, and is responsible for investment and implementation in major infrastructure projects.

A study by ESD et al. (2007) found a lack of adequate EP frameworks as responsible for current sub optimum, ad-hoc, short-term decision making being made in the energy sector of SSA. The work found that coherent medium to long-term EP considered important for the development of energy trajectories for developing countries was largely absent from the countries studied in SSA.

In countries without long-term energy policies or where implementation efforts have been stalled, additional fuel-oil power plants are often hastily installed to meet demand requiring more energy imports and further complicating energy security concerns (Siyambalapitiya, 2002). When installed generation capacity is insufficient short-term actions may be required, forcing governments to invest in options such as emergency power generators (Kpodo, 2015). Emergency power generation can be costly and require additional oil imports. In 2007 emergency power generation accounted for 5% of total installed capacity in Ghana at a cost equaling 1.9% of its GDP (Eberhard A. et al., 2008).

The effects of climate change are not spread equally over the globe and different regions will experience dissimilar affects. Despite the low total and per capita emissions attributable to many developing countries such as those of SSA, long term impacts and risks of climate change for their populations are of particular concern due to the likelihood that poorer populations may become increasingly vulnerable. SSA's energy sector is also at risk due to the region’s dependence on biomass as a FE carrier and hydropower for electricity generation. Changes in precipitation may result in losses, or variability, in hydroelectric power generation potential as well as decreased biomass production (IPCC, 2001; World Bank and UNDP, 2005).

Authors have suggested that innovative policy frameworks need to be developed and implemented in order to achieve ambitious energy access and related targets. There is a need for a framework that establishes coherent policies with precise targets and strategies to reach them (Brew-Hammond, 2010; Kemausuor et al., 2011).

Efforts to address this problem and establish energy policies are, or should preferably be, based on the outputs of EP activities that are based on methodologies and models that are adequate for the geographic context. Attention should be paid to setting objectives that are specific to the contextual realities of the location of EP, requiring actors to develop specific objectives, avoiding the adoption of a generic set of objectives that may not prove to be relevant.

While the EP activity and policy development has typically been focused on independent national energy systems, recent activities to regionalize energy markets and systems have promoted co-operation with neighboring countries. These activities have resulted in the development of regional power pools and international gas pipelines. Planning activities can take advantage of these energy sources to fuel increased generation capacity, diversify PE resources, as well as other potential benefits (IEA, 2014a).

1.1.4 Decision making in energy planning

The planning activity has been described as anticipatory decision making as it is a process through which, based on a set of preferred outcomes, courses of action are selected in a series of interrelated choice situations expected to occur in the future (Sagasti, 1988). It is possible then to view the EP activity as a decision problem in which a method is needed by actors to evaluate potential actions in their fulfillment of established objectives.

Beyond the multiple objectives that are set for the EP activity, actors must also consider and model multiple technical measures (e.g. electricity generation plant types, and promotional mechanisms such as efficient appliance rebates) to assess the potential for different alternative mixes to achieve the objectives. For this DMs need to translate objectives into quantifiable attributes that allow for evaluation of technical measures and promotional mechanisms within the context of constructed alternatives.

The EP activity, according to van Beeck (2003), is a decision making process comprising the steps of (1) Problem identification, (2) Identification of the relevant alternatives, (3) Assessment and comparison of alternatives, (4) Appraisal of alternatives, and (5) Selection of alternative. This definition adapted from the work of Carpenter (1987) and Georgopoulou et al. (1997) restricts the EP process to the selection of the preferred alternative and does not include the possible next steps required to implement the EP alternative or the monitoring and evaluation of the plan outcomes in support of future activities.

Rad (2011) presented a similar structure of EP as a decision process based on the work of Ackoff (1970). This structure expanded the scope of planning to include the steps of (1) implementation and (2) measurement and verification. Implementation concerns consist of the organization of the EP activity and structuring of the decision making procedure in a manner that the final plan can be executed successfully. Monitoring and evaluation is the last step in the list, but preferably not the final, as it will provide information about the outcomes to support the sequential planning phase.

Energy policies in developing countries will have to address how modern energy access targets and other developmental objectives are to be achieved while ensuring that energy demand and the energy supply are balanced. They must also overcome specific geographical contextual constraints.

The objectives for the EP activity are also not static over time and those considered vital today (e.g. to maximize energy security and minimize impact on global climate) may change in the future. Access to electricity, today universal in developed OECD countries, was recently a development objective. As recently as 1930 in the United States 68% of households and 10% of farms had access to electricity and annual consumption was approximately 547 kWh/capita. Access rose to 94% and 78% for households and farms respectively in 20 years (1950) due to objectives to increase access to electricity (Kitchens and Fishback, 2013; USCB, 1975).

These multiple concerns imply that the EP activity cannot be approached as a single objective problem (i.e. maximizing the access to modern energy services) but should be seen as a multi-objective decision process with a goal of ascertaining the correct, or most adequate, mix of actions to be taken to best achieve a set of objectives that in some cases may be conflicting (Haydt, 2012; Pohekar and Ramachandran, 2004).

1.2 Research objectives and questions

The central purpose of this research is to make a contribution to national EP practices in developing countries, where the member countries of the ECOWAS in SSA will be used to narrow the focus on a representative area of study. More precisely, the purpose of this research is to identify specific EP objectives together with their relative operational attributes, to structure these within a transparent multi-objective decision making methodology for EP at the national level, and to assess whether these specific objectives make a difference in the EP activity

A hypothesis of this research is that specific objectives may exist, beyond those that are commonly considered in the elaboration of energy plans, that are especially relevant for the local context of EP in developing countries and specifically the ECOWAS region. It is also hypothesized that when these additional EP objectives are explicitly considered in national EP activities, the resulting selection of desirable alternatives may differ from those that would have been selected from methodologies that solely adopted the commonly considered EP objectives. Finally, an EP methodology that identifies these additional EP objectives may aid in ensuring the implementability and sustainability of energy plans and policies.

Three research questions were formally established to guide the work.

1. Are there EP objectives specific to the local context that influence the successful implementation of energy plans?

2. If these specific objectives exist, what quantifiable attributes can be employed to make them operational within the EP structure?

3. How do the results from an EP methodology including these additional objectives differ from those from a methodology including solely the base objectives?

1.3 Research scope and limitations

1.3.1 Scope

The methodology will be developed for application within the context of the ECOWAS member states. While the methodology has been designed for countries of the ECOWAS region, these countries share many developmental and energy sector specific traits with other developing countries, and so there is the potential for it to be adapted to countries of other regions.

The scale of EP activities can be separated into five levels, from the local scale (e.g. towns or municipalities), to the regional scale (e.g. multiple municipalities in a country), to the national scale, to the regional-international scale, and finally to the global scale.

Rad (2011) surmised that most developing countries conduct national EP and that industrialized countries support lower levels of community EP. However, as the following Chapter 2 will show, the national EP activity is often absent in ECOWAS member states. The EP activity in developing countries is typically a mandate of the central government as the main decision maker, while local and regional governments lack the authority to make decisions and the appropriate data to conduct EP. In addition, local and regional energy systems are part of the larger system and typically cannot be operated in isolation (Løken, 2007a). Planning efforts at the national level may be required to set the agenda for future efforts at the local level.

The current work is being undertaken with a focus on supporting national energy policy development. It is assumed here that EP activities at the national scale, with a government's backing, have the potential to induce change at subsequently smaller scales within the country, based on the assumed authority, technical competencies, and financial abilities of actors at this level. Despite the diverse group of actors involved in the EP activity, national governments still hold significant influence over the energy sector. Governments have the ability to support specific programs and enact policies that promote energy conservation. These programs can include audit programs, technology demonstration programs, incentives, grants and funds (World Bank, 1993). At the national level, EP can support policy making that in turn provides a roadmap or vision for the energy sector at subsequently smaller levels, as well set national strategies for regional and international energy relations.

Construction at the national level scale, however, must also reflect the diversity that exists at local levels. It is the diverse local regions that together form the collective nation. Characteristic areas such as urban, peri-urban and rural areas must therefore be considered in the model.

Modeling the energy systems at the national level necessitates consideration of the energy system from the supply of PE to the FE demand. The development of comprehensive energy plans requires the inclusion of the various PE supplies to the energy sector, the transformation processes for the energy sector, the full spectrum of FE carriers provided, the energy demand sectors and energy services demanded within the country. Outside the scope of the current work are efforts to alter the specific individual technologies that provide for energy services (e.g. electric and gas water heaters, or compact fluorescent lamp vs. incandescent lamps) as there are many technological options available.

Energy plans are not implemented instantaneously, and depending on the project lead times of the activities or infrastructure required, the time horizon for completion can vary from a short (approximately 1-5 years) to a mid (approximately 5-20 years) or to a long time horizon of 30 years or more.

A mid-range time horizon provides for development of infrastructure that potentially requires a number of years to complete as in the case of electrical energy systems. It is also short enough to make corrections if needed, as these systems are dynamic and unforeseen events may require direction changes in the energy plans. This time range also does not require intensive planning resources, which may be required if the EP activity is conducted more frequently, as may be the case for shorter time horizons. The description of the energy supply and demand model will be limited to the specifications described previously, namely a national level planning effort for the mid-range time horizon.

There has been a general trend worldwide, as in SSA, towards liberalization and privatization of state own utilities (Bennell, 1997; Gualberti et al., 2009). This includes efforts to establish independent regulators and allow for independent power producers (IPPs) in the electricity sector. Policies and regulations have been established to develop market incentives for the inclusion of renewable energies in energy systems. Additionally, policies and regulations have been established as parts of international efforts to limit GHG emissions and global and local environmental impacts attributable to energy systems (UN-Energy, 2007). The current work, while constructing a model of the national energy system and developing policy alternatives, does not purport to include any changes to specific regulatory frameworks at the national level. It is limited in scope to the modeling of general and generic energy policy pathways.

The energy system is a capital intensive system requiring large investments over long periods of time. The current work does not include considerations of financing mechanisms, such as the Clean Development Mechanism that allows signatory developed countries to offset emissions through investments in clean generation technologies in developing countries. Additionally, it does not attempt to model or recommend any energy pricing policies. The work is not intended to predict pricing policies that are politically motivated, energy taxing policies for revenue generation, or energy markets that do not function efficiently although all of these factors can affect the outcomes of the policies put in place (Bhattacharyya, 2011).

The development of energy systems requires training of human capacity, education, and research at many levels. The current work does not seek to identify the level of current capacity or required future human capacity or education levels that will undoubtedly be required as countries develop their energy system infrastructures.

1.3.2 Limitations

The current work is focused on EP objectives within developing countries. In order to narrow the focus of this work, the ECOWAS region was selected as a representative area of study. Likewise, the case study developed within the context of this research will be limited to one ECOWAS member state. The results/recommendations of the case study cannot be immediately generalized for all developing countries. However, the methodology is directly applicable in the context of national EP activities countries of the region.

The model developed in this work was not constructed to predict the future or make definitive decisions as to the best alternatives or choices for the energy planners, but as a decision aid tool. The research questions ask if the implementation focused methodology provided differing results as opposed to methodologies employing traditional objectives, and so the results from this methodology cannot be said to prove one methodology is more advantageous than another.

While this work may aid in the development of energy plans, it cannot ensure the success of the EP objectives or other national policy objectives, economic, social, or environmental as there are influential external factors such as political interests or economic constraints, which may be unforeseen. Undoubtedly an additional and no less important characteristic of implementation of EP options is political interest. Due to the fluxes within government, this interest is difficult to predict. This characteristic presents an uncertainty that the current work will not directly characterize with an attribute, but instead provide for with an interactive approach with DMs and multiple alternatives in the formulation of an energy plan.

1.3.3 Contribution

In broad terms this work may aid international efforts to increase modern energy access, and thus help to improve the lives of populations in developing countries by supporting economic and human development and environmental protection.

More specifically, this new methodology contributes to EP research and practice by giving more emphasis to the implementability of energy plans specifically in developing countries. The methodology and the current thesis explore the process of identification of EP objectives that are specific to the context and the effect that these have in the evaluation and choice of attractive EP alternatives. This is a contribution with potential impact beyond the scope of only ECOWAS and developing countries.

Contributions will be made to furthering EP research in the energy sector of SSA and other developing countries. Additionally, this work will establish a novel EP methodology supporting the development of coherent national energy policies in developing countries. Currently a methodology of this type for national level EP appears to be practically absent in the practices of the ECOWAS region.

1.4 Thesis organization

The current introductory chapter described the main motivations, introduced the research objectives and questions, and defined the scope and limitations of the thesis.

The state of the art of the EP practice in developing countries is presented in the chapter that follows, Chapter 2. The literature review that this chapter consists of begins with a review of EP practices in SSA, before providing a systematic review of recent activities in West African Countries.

The development of a national EP methodology is presented in Chapter 3. This chapter begins with a review of existing frameworks, before discussing the problem structuring, energy modeling, EP alternative development, and finally the multi-criteria evaluation methods to be employed.

Chapter 4 details the construction of a national energy system model. The chapter presents the considerations for modeling both energy demand and supply at the national level. The considerations necessary for the development of a reference energy demand and supply projection are discussed together with preliminary data from the case study that follows.

Part I of the application of the national EP methodology is presented in Chapter 5, which begins with a description of the purpose of the real world application in a case study. The country chosen for the case study is presented together with an overview of its energy sector. Part I consists of the application of the energy model for the case study country and the development of a reference projection. A set of EP alternatives are also presented and discussed in detail.

Chapter 6 presents Part II of the application of the national EP methodology in which the EP alternatives modeled in Part I are evaluated in their achievement of the EP objectives within the decision support methodology. A decision conference (DC) hosted for the case study country case study is described together with the application of the multi-criteria decision assessment model in the evaluation of the EP alternatives. A sensitivity analysis on the preliminary results is conducted before providing a summary of the results.

The final chapter, Chapter 7, presents the conclusions of the thesis in regards to the energy system model developed, the case study insights, the research objectives and questions, and the implications of the work. The contributions of the thesis are presented in terms of general EP concerns and additional real world policy implications. The future lines of research considered important based on the conclusions from this work are presented.

Chapter 2

Energy planning practices and methods in developing countries

2.1 Introduction

The EP activity is one that falls predominantly into the category of applied research as opposed to basic research. Friedmann (1987) described planning as *“an attempt to link scientific and technical knowledge to actions in the public domain.”* Basic research related to EP is predominantly focused on improving the understanding of the role that energy plays in society and improving models that comprise the overall EP activity. The state of the art advances with both basic research and the continued conduction of EP by actors involved. The state of the art is therefore depicted by a structured review of current EP practices and the methods implied in their practice.

The Economic Community of West African States (ECOWAS) members, although a diverse group of nations, face many of the challenges to economic and human development common to other developing countries. The ECOWAS was selected to narrow the focus of the analysis while maintaining a significant and representative sample of developing countries.

The purpose of the current chapter is therefore twofold. First, a depiction is made of the current state of EP practices in developing countries through a literature review of EP activities completed in Sub-Saharan African countries and specifically ECOWAS members. A systematic review at the regional (multiple countries), national and local scale within the ECOWAS region has not been performed previously to the best of the author’s knowledge. Secondly, it draws on this understanding to identify gaps in the current state of the art and to develop recommendations to guide the current work in establishing an effective methodology to support future EP activities.

2.2 Energy planning and implementation

There has been an inconclusive debate about the steps that comprise the EP activity. Van Beeck (2003) argued that the EP activity closely follows that of a decision making process and could be deconstructed into a similar set of steps. This decision process was broken into five main components; (1) problem identification, (2) identification of relevant alternatives, (3) assessing and comparing alternatives, (4) appraising alternatives, and (5) finally selecting an alternative. The remaining phases of implementation and measurement and verification followed after the final step of the decision making process, and therefore Van Beeck (2003) argued for this to not be part of the planning activity by definition.

Rad (2011) claimed that the planning activity also includes both implementation and the control or measurement and verification of plan success. Including these additional components the EP activity can be seen as consisting of three central phases. First is the elaboration of the energy plan. Second is plan implementation. And finally is the measurement and verification of the plan. The final phase also supports subsequent planning activities. Achieving the EP objectives declared in the first phase is dependent on successful realization of all three phases.

In order for the second phase to be accomplished, a number of implementation barriers must be overcome (FAO 1990). EP often entails the import and use of foreign technologies in developing countries, and this often leads to subsequent abandonment of the technology or project due to unforeseen barriers (Dunmade, 2002). Projects may fail prior to, or shortly after, completion resulting in unfulfilled EP objectives in addition to lost investments. Energy sector projects are often capital intensive with large lead times for completion resulting in large financial losses when not realized. Dunmade (2002) described that energy sector projects in Nigeria commonly fail prior to, or shortly after, completion, resulting in expensive projects to be left to rust and large financing efforts spent on unrealized objectives. The success rate of World Bank financed electric power projects in SSA was reported to be 36% as opposed to a general rate of 68% (Dunmade, 2002; World Bank, 1996). A review of the sustainability of energy sector projects with World Bank investments in SSA from 2000-2013 found that 30% of the reviewed projects were either Unlikely or Highly Unlikely to have sustainable benefits, compared to a 15% of reviewed projects (Unlikely or Highly Unlikely) World Bank wide (World Bank, 2013b). Aliyu, Ramli, and Saleh (2013) argued that the underutilization of electricity plants in Nigeria was caused by a number factors including a lack of trained manpower, lack of manufacturing capacities of spare parts, and insufficient funding.

Unsuccessful implementation and unsustainable energy systems have large ramifications for economies. In 2012, 40% of the installed capacity in Nigeria was unavailable resulting in large amounts of unmet demand (Castellano et al., 2015).

To meet energy demand in countries lacking long-term energy policies or where implementation efforts have been hindered, additional fuel-oil power plants have often been hastily installed. While this may aid in meeting demand, it also increases energy import requirements and further complicates energy security concerns (Siyambalapitiya, 2002). Additionally, emergency power generation can be costly and require additional oil imports, as was the case in Ghana where emergency power generation accounted for 5% of total installed capacity and was estimated at 1.9% of GDP in 2007 (Eberhard A. et al., 2008).

The EP activity, for the current work, is considered to be separated into three main phases. The first phase is the plan elaboration, which includes both the technical development as well as the decision processes. The second phase is that of plan or policy implementation, consisting of both the initial execution of actions following plan elaboration as well as the continued use of the energy technologies and systems introduced in the actions. The third, but preferably not final, phase is the monitoring and evaluation activities that should be conducted as an ongoing process to determine planning and policy successfulness as well as to support future EP activities.

2.3 Energy planning practices in sub-Saharan Africa

The countries of SSA are facing formidable challenges to economic and human development, for which energy plays an essential role. To achieve medium to long-term EP objectives innovative policy frameworks are required. These must establish coherent policies with precise targets and be based on clearly detailed EP strategies (Kemausuor et al., 2011).

A limited amount of research characterizing the EP activities of developing countries and more specifically those of SSA has been conducted. The study from ESD et al. (2007) provided the only work specifically analyzing the EP practices in developing countries of SSA.

The countries of SSA have been found to lack adequate frameworks to conduct medium to long term EP, and the EP practice was found to be relatively nascent. ESD et al. (2007) concluded that the absence of adequate EP frameworks has led to deficient, ad-hoc, and short-term decision making in place of coherent medium/long-term EP. Frameworks for EP were found to be weak, disjointed or largely absent in the countries reviewed. In this absence, short-term and/or immediate concerns of ensuring energy security and supplying sufficient and reliable energy for development took precedence with actors. The ECOWAS Center for Energy Efficiency and Renewable Energy (ECREEE) (2012a) also propounded the view that EP policy development, in the ECOWAS region specifically, was hampered due to largely non-existent or weakly implemented institutional structures and frameworks. These inadequate EP activities do not support successful energy policy development.

The lack of adequate EP frameworks adversely affects successful implementation of the resulting energy policies. ESD et al. (2007) found a gap between energy policies being elaborated by governments and the actual implementation of these policies. This was due to a separation between the actors responsible for implementation (e.g. finance and planning ministries and national utilities) and those supporting policy design (e.g. energy and environment ministries or commissions conducting the EP exercise). Frameworks must improve the integration of the broad array of stakeholders involved in EP and promote ownership and assign responsibility for the eventual implementation of EP.

Unsuccessful implementation of the energy policies was also found to be caused by an inability to clearly identify the objectives of the EP activity. The key EP objectives for the region were identified in the review as energy access, energy security, and climate change (ESD et al., 2007).

Stakeholders interviewed by ESD et al. (2007) expressed a need for medium to long-term EP frameworks that incorporate energy supply and demand forecasts developed within applicable models. These should also allow for evaluation of various EP alternatives, as representations of policy mixes, in performance of the stated EP objectives.

Energy master plans have not been the focus of EP activities in SSA. The general focus of EP activities conducted by utilities and governments in the region have been on the electricity sector and centralized grid power systems (ECREEE, 2012a; ESD et al., 2007). Many resources are provided for electricity sector development, while the biomass sector, which supplies FE to meet the larger share of FE services for populations in the region, is largely ignored. Planning activities centered on liquid petroleum based fuels (e.g. kerosene, LPG, and diesel) have also been devalued, and suppliers in the region were found to respond directly to market demands (ESD et al., 2007).

Inadequate EP frameworks have also been linked to a shortage in trained staff with the qualifications to conduct EP activities (ESD et al., 2007). This has led to an absence of advocacy for, as well as an understanding of, the important role that EP plays in development. In addition, this lack of skills has led to deficiencies in energy data analysis, energy demand forecasting capacity, and the ability to develop EP alternatives to support policy development. Complicating the EP process further is the absence of data and information required for the development of future scenarios and policy alternatives in the EP activity (ESD et al., 2007).

2.4 The Economic Community of West African States (ECOWAS)

The Economic Community of West African States (ECOWAS) is a community comprising 15 member states located in the Sub-Saharan West African region presented in Figure 2-1. The 15 member states are Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

Figure 2-1 - Map of the Economic Community of West African States (ECOWAS) (Natural Earth, 2014)

2.4.1 Socio-economic situation

The ECOWAS region covers approximately 17% of the land area of the African continent. While the states are members of a single community and face many similar challenges, they represent a very diverse group, and diversity exists both between the members and within the borders of each individual member state. The largest states, Mali and Niger, have land areas over 1.2 million km^2 and 1.3 million km^2 respectively while Cape Verde has an area of 4,000 km^2 (World Bank, 2011a). There is one island nation, Cape Verde, and three landlocked states, Mali, Niger and Burkina Faso.

In 2010 the ECOWAS population was 301 million people, a number forecasted to reach 395 million by 2020.[8] Nigeria, the most populous state, had a population of 160 million in 2010. Ghana, the second largest population, had 24 million. The remaining states had populations between 1 and 16 million people. Cape Verde had a population of fewer than 500,000 people (UN, 2013).

13 of the 15 member states were classified within the Low Human Development group by the UNDP, with the exception of Cape Verde and Ghana, which were classified in the Medium Human Development Group (UNDP, 2014). All the members were classified as Least Developed Countries, except Cape Verde, Ghana, Ivory Coast and Nigeria by the United Nations (UNCTAD, 2014). All 15 members were classified by The World Bank as part of the low income group, except for Cape Verde, Ivory Coast, Ghana, Nigeria, and Senegal, which were in the lower-middle income group (World Bank, 2015b). The ECOWAS countries were classified by

[8] The 2020 population projection is based on the medium fertility assumptions in (UN, 2013).

the International Monetary Fund (IMF) as Emerging and Developing Economies, and 13 of them held the status of Heavily Indebted Poor Countries (IMF, 2015b).

2.5 Methodology

2.5.1 Document gathering and filtering

The literature review on EP activities in the ECOWAS region began with a process of gathering EP documents. EP documents are defined here as works that require energy sector actors to make assumptions about future scenarios and to develop quantified energy demand forecasts. They are considered distinct from Energy Policy and Program Specific documents. The literature review was conducted in the period of September of 2011 to January of 2012.

EP documents provide the data and information necessary for the elaboration of Energy Policies and Program Specific documents. Energy Policies are those that lay out the desired vision for energy demand and supply and the strategies that will aid in the achievement of this vision. Energy Program Specific documents are those that focus on specific energy resources or technologies and the implementation of specific projects. The current review only includes EP documents as defined above, and excludes Policy or Program Specific documents. Policy documents are considered too general to provide insights into the EP practices, while Program Specific documents are quite specific in scope and lack representativeness of the EP practices.

A comprehensive online search was conducted to gather EP documents from all ECOWAS members for multi-state regions, countries, or cities or municipalities available from sources that included governments, government institutions, international organizations, and academic research journals. After searching these sources and following references cited in the works recovered, a point was reached when no new documents were identified.

This collection process gathered 51 documents that are listed in Table E- 1 of Appendix E. From this set, Energy Policy and Program Specific documents were eliminated and only EP documents, as defined above, were considered for the analysis. The filtration process is presented below in Figure 2-2. This resulted in 14 of the total 15 EP documents that are presented with the results in Table 2-1.

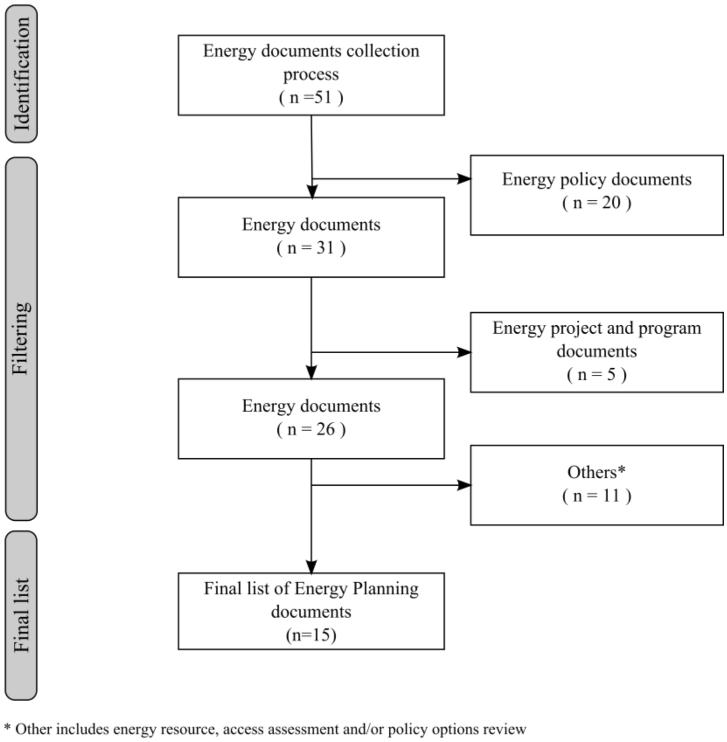

Figure 2-2 – Flowchart of EP document literature review

Limitations exist to an online document search, as not all EP documents are available online from the governments, institutions, and other organizations of countries in the ECOWAS region. To bolster the search effort a survey was conducted in cooperation with the ECREEE. For this survey 15 official National Focal Institute (NFI) contacts of the ECREE, representing each of the ECOWAS members were asked about their knowledge of existing national, city or municipality, and other EP documents for their country as well as their ability to provide these documents. The inquiry, translated into respective official country languages of the region, was provided to the NFI contacts through the ECREEE.[9]

A total of 6 responses were received within 29 weeks of sending the surveys to the 15 NFI contacts. The survey process provided information on an additional 22 documents. From these, only one document considered an EP document had not already been recovered from the online search. This document was added to the previously recovered EP documents, making the total number of documents to be reviewed 15.

The 15 EP documents recovered are presented, together with the results in Table 2-1. The document numbers included are used to avoid confusion, and no preferential order was given to documents in the list.

[9] The staff of ECREEE in Praia, Cape Verde provided aid in the process of surveying the 15 National Focal Institute (NFI) contacts in the ECOWAS member states, and thanks must be extended to them and the NFI contacts. Thanks are due to Sara Magalhães at the University of Porto, Engineering Faculty for her effort in translating the ECOWAS NFI contact surveys for this work.

Table 2-1 - EP documents and type

Doc.	Country	Document Name	Reference	Document Type: Energy Master Plan	Document Type: Electric System Plan	Document Type: Env. Protection Plan	Document Type: Basic Energy Services Plan
D1	Cape Verde	National energy plan	(MECC, 2004)	√			
D2	Ghana	Strategic national energy plan	(EC, 2006a)	√			
D3	Benin	Strategy for the Supply of Energy Necessary for the Achievement of the MDGs	(MDEF and MEME, 2006)				√
D4	Gambia	Master plan for renewable energy based electricity generation in The Gambia	(Flores, 2010)		√		
D5	Nigeria	Assessment of energy options and strategies for Nigeria: Energy demand, supply and environmental analysis for sustainable energy development (2000-2030).	(ECN and IAEA, 2006)		√		
D6	Senegal	Economics of greenhouse gas emissions	(UNEP Risø and MENP, 2001)			√	
D7	Nigeria	Electricity demand forecasting in Nigeria using time series model.	(Mati et al., 2009)		√		
D8	Liberia	Simplified power system master plan - a primer for decision-making	(NORAD and MLME, 2009)		√		
D9	Togo	Support program for the control of traditional energies and the promotion of renewable energies in Togo	(MERF et al., 2008)			√	
D10	Sierra Leone	The Sierra Leone energy sector: prospects & challenges	(MEP, 2006)		√		
D11	Ghana	Assessing policy options for increasing the use of renewable energy for sustainable development: Modelling energy scenarios for Ghana	(UN-ENERGY et al., 2006)		√		
D12	WAPP*	Update of the revised master plan for the generation and transmission of electricity	(ECOWAS, 2011)		√		
D13	Nigeria	Renewable energy master plan	(ECN and UNDP, 2005a)	√			
D14	Cape Verde	Renewable energy plan of Cape Verde	(DGE, 2011)		√		
D15	Ivory Coast	Strategic development plan 2011-2030: Electricity and new and renewable energies	(MMPE, 2011)		√		
			Count	3	9	2	1

*West African Power Pool (WAPP)

2.5.2 Matrix of analysis

A matrix of analysis was constructed to provide a systematic methodology of review of the documents (Table 2-2). Four main questions provided a structure for the analysis.

The first question asked who was active in the EP activities. The aim of this question was to establish an understanding of which ECOWAS members have conducted EP activities as well as what actors, foreign or local, contributed to the activity, together with the nature of their contribution. The contributions considered were either technical support or management of the EP activity.

The second question addressed the purposes of the EP activities. This provided an understanding of the type of activities that were being conducted (e.g. environmentally focused, power system focused, or other). In addition, this question allowed for characterization of the objectives that were set for the EP activity, the attributes used to pre-assess planning alternatives, and the indicators presented for measurement and verification activities.

Table 2-2 - Matrix of analysis

1 Who is active in EP?	2 What is the purpose of EP activities?	3 How is energy demand considered?	4 What is the scope of the EP activities?
1.1 Which ECOWAS member states have EP documents?	2.1 What types of EP activities are being conducted?	3.1 How is energy demand forecasted?	4.1 What modeling tools are used?
1.2 What actors are involved in the planning activities?	2.2 What are the objectives of the EP documents?	3.2 What factors are considered in the demand forecast?	4.2 Which PE sources and FE carriers are considered?
	2.3 What attributes are used in the EP process?	3.3 Are distinctions made between Urban and Rural energy demand?	4.3 Are environmental consequences of energy demand forecasts quantified?
	2.4 What indicators are used for measurement and verification?	3.4 How long are the planning horizons considered?	
		3.5 How many scenarios are considered?	
		3.6 How many alternatives are presented in demand forecasts?	
		3.7 Are considerations of energy DSM measures made?	

The way in which energy demand was considered is examined in the third question, exploring the data requirements, geographical considerations, planning horizons, the scenarios constructed and the planning alternatives considered.

The final question explored the scope of the activity with a look at the available planning-assisting models and tools (e.g. models and methodologies) cited in the works. It also characterizes the PE sources considered in the works as well as the secondary/FE carriers. Also, a review of which environmental consequences were quantified as part of the planning alternatives considered was conducted.

The level of specificity of energy based indicators employed in the documents was also explored. Two sets of energy sustainability indicators for local EP in more developed countries, presented in Neves and Leal (Neves and Leal, 2010), were used for juxtaposition with those found in the EP documents of ECOWAS.

2.6 Results from ECOWAS EP review

2.6.1 Who is active in EP?

Which ECOWAS member states have EP documents?

Both the presence of as well as the absence of an EP document are important to note, as this represents the capacity and efforts required to provide input to energy policies.

Of the 15 member states, EP documents, within the criteria defined (i.e. having quantification and demand forecast) were recovered for 10 countries and the West African Power Pool (WAPP). Table 3 presents the EP documents types recovered. Two documents were encountered for Cape Verde, Ghana and Nigeria.

What actors are involved in the EP process?

A breakdown of the actors involved in the initiative and process management, and in the technical analysis is presented in Figure 2-3. Here "local" refers to those based within the country.

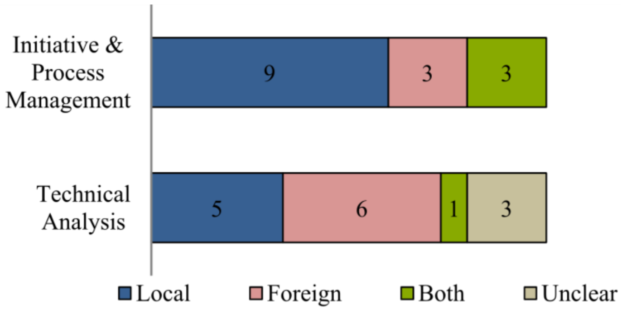

Figure 2-3 - Actors involved in the EP activities

Initiative and process management actors were predominantly local actors, where 9 of 15 documents had only local actors and 3 had both local and foreign initiative. The technical analysis effort was closely divided between foreign and local actor involvement, in 6 and 5 of the documents respectively. The technical analysis effort, coming either from foreign or local actors, was considered unclear in 3 of the documents, D6, D9, and D10 (note: document labels refer to Table 2-1).

An assessment of the number of actors involved in the individual documents is presented in Figure 2-4. The majority, 12 of the 15 documents included the involvement of more than one actor. Collaborations between local and foreign actors were found in 11 of the 15 documents.

Two of the documents reviewed were academic documents, D4 and D7. D4 is a foreign doctoral student's thesis focused on Gambia's electrical energy system. D7, an academic article, had authors in two separate university departments, counted as two local actors in

Nigeria. D6 is a United Nations Energy (UN-Energy) study for Ghana that included a collaboration of separate international agencies. D14 is an EP document from Cape Verde with multiple foreign actors.

A breakdown of foreign and local actors involved in the initiative and process management is presented in Figure 2-5. The most common local actors found were government ministries, government agencies, e.g. national energy commissions and national statistics institutions. The most common foreign contribution was from international organizations (e.g. the UN).

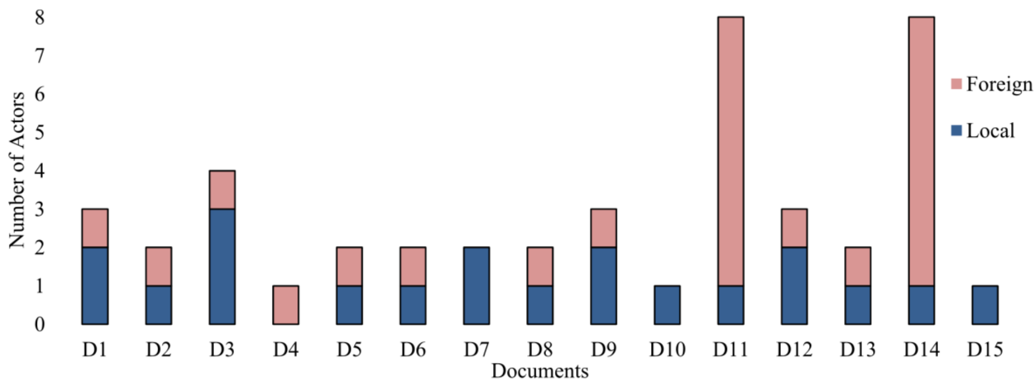

Figure 2-4 - Number of actors involved per document

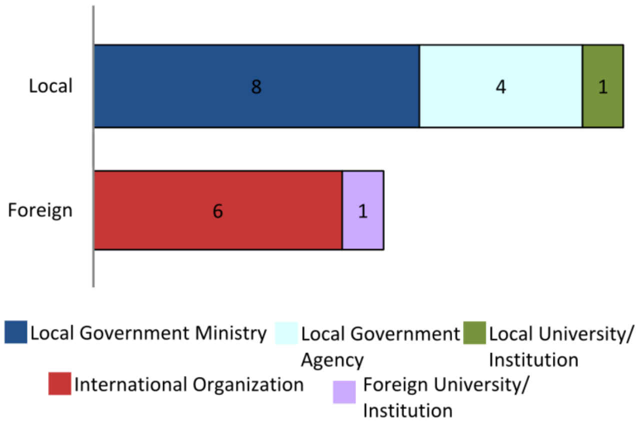

Figure 2-5 - Breakdown of Initiative and Process Management actors

A disaggregation of the initiative and process management actors by document is shown in Figure 2-6. Local government ministries were involved in 8 of the 15 documents and government agencies in 4 of the documents. Multiple government ministries were also involved in 3 of the documents. Here collaborations between local government ministries or agencies and international organizations were found in 4 of the 15 documents.

The breakdown of technical analysis actors is presented in Figure 2-7. The technical effort was unclear in 3 of the documents, and these were not included in the figure. Local government ministries were involved in 2 of the documents, and government agencies were found in 3 of the 15 documents. Foreign contribution from consultant/companies was found in 4 of the 15 documents while both international organizations and foreign universities were found in 2 of the 15 documents.

The technical analysis actor type by document is presented in Figure 2-8. Here foreign consultant/companies were involved in 4 of the 15 documents, and government agencies were involved in 3 of the documents. Document D11 was a collaborative effort from the UN-Energy involving multiple actors such as the International Atomic Energy Agency (IAEA), Department of Economic and Social Affairs (DESA), Food and Agriculture Organization (FAO), United Nations Environment Programme (UNEP), United Nations Industrial Development Organization (UNIDO), and the World Bank. The actors involved in D14 also included multiple foreign consultants.

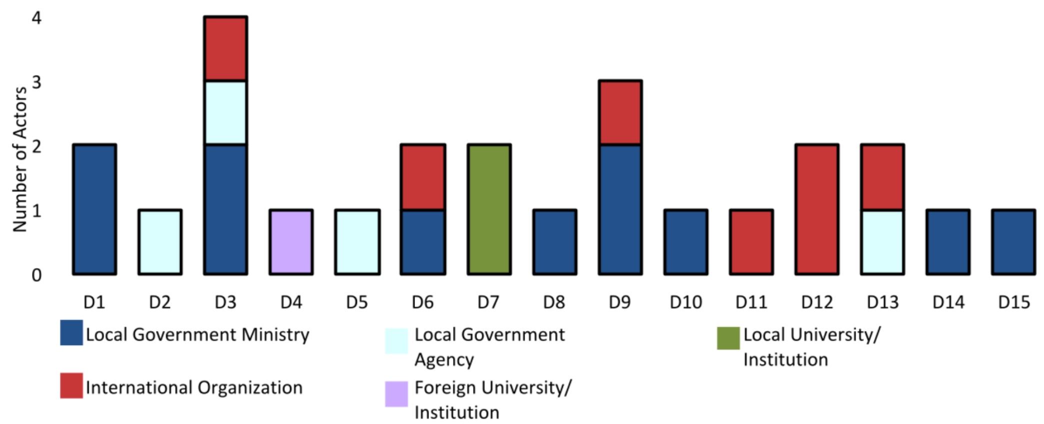

Figure 2-6 - Initiative and Process Management Actors by document

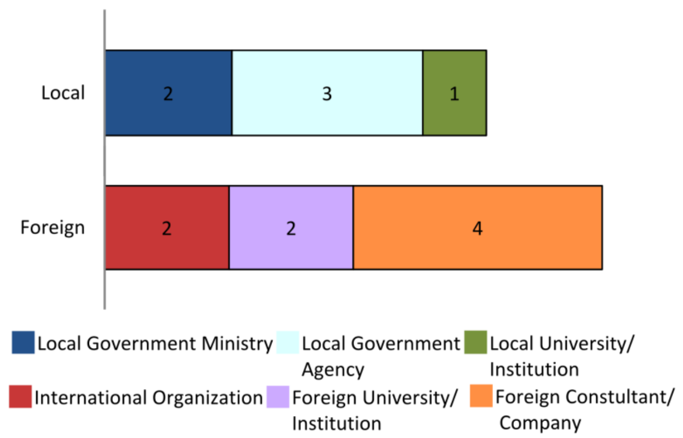

Figure 2-7 - Breakdown of Technical Analysis actors

2.6.2 What is the purpose of the EP activity?

What types of EP activities are being conducted?

The EP document types recovered can be characterized within 4 categories. *Energy Master Plans* include forecasts of multiple energy carriers, demand sectors, end-uses, and possibly PE sources for the country. *Electrical Systems Plans* specifically consider electrical energy systems, which may include multiple demand sectors, end-uses, and PE sources or be specific to renewable energy sources for electricity generation. *Environmental Protection Plans* have environmental planning focuses, and include energy demand projections for this end. *Basic Energy Services Plans* focus on the provision of energy services for development, and more closely resemble policy documents outlining government goals for energy access and include energy demand forecasts. This final category differs from *Energy Master Plans* that are more all-encompassing and present forecasts for multiple energy carriers, sectors, end-uses and PE sources.

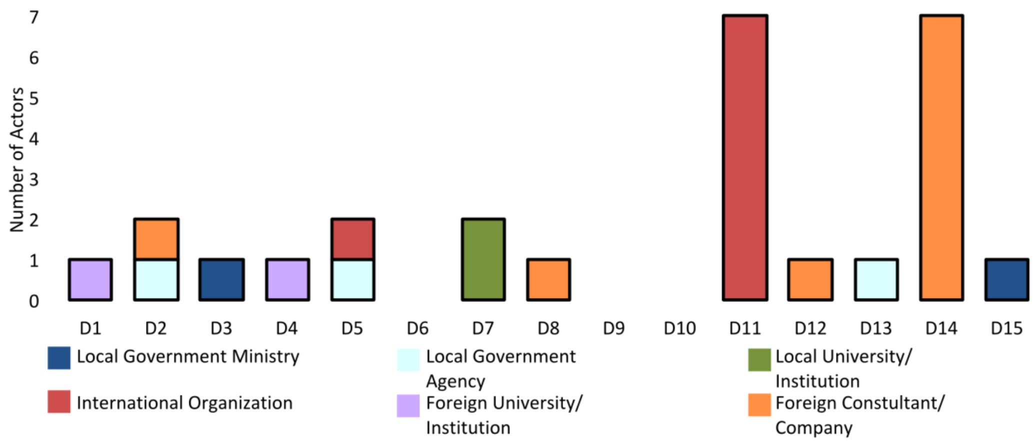

Figure 2-8 – Technical Analysis actors by document

Nine of the 15 documents in Table 2-1 were *Electrical System Plans*, the most common EP document type. *Energy Master Plans* were the second most common, followed by *Environmental Protection Plans*. There was one *Basic Energy Services Plan*.

What objectives are set for the EP activity?

The EP activity, like any complex problem, should be structured around a number of objectives that set the overarching purposes for which the activity is undertaken. These objectives should then be reflected throughout the EP process. The terms *objective*, *goal*, and *target* are frequently used interchangeably in colloquial language. The term *objective* here, following Keeney (1992), refers to a statement of what is hoped to be achieved. It requires three components: a decision context, an object, and a direction of preference. For example, for the national EP activity an objective may be "*To minimize GHG emissions*." The decision context is the national EP activity, the object is GHG emissions (possibly the impact on global climate), and the preference is for less GHG emissions as opposed to more. The terms *target* and *goal* refer to the introduction of a specific level or standard in the measurement system in regards to an objective. The *goal* or *target* is either achieved or not achieved. An example of a *target* or *goal* would be to decrease the GHG emissions to 20 kton of CO_{2eq} by the end of the planning horizon.

The objectives include both *fundamental* and *means* objectives. Following the Value Focused Thinking method, *Fundamental* objectives are those that are both essential and controllable objectives, while *means* objectives are those that are important due to their implications for other higher level objectives (Keeney, 1992). Identification of *fundamental* and *means* objectives lies in the answer to the question "Why is this objective important?" Keeney (1992) specified two possible answers, the first being that the objective describes a core reason for interest in the problem, meaning it is a potential *fundamental* objective. On the other hand, if the answer to the question brings an additional objective to light it is a *means* objective.

Structuring of objectives in a decision problem, as described by Keeney (1992), aids in defining the objectives, relating them to one another, and relating them to yet to be identified objectives. This is typically to be done within a specific decision context at the start of the EP activity. For this work, however, an effort is made to structure the *fundamental* objectives, in order to identify the objectives stated within a common frame of reference.

To establish a list of *fundamental* objectives it was necessary to identify the *fundamental* objectives that were implicitly referred to through the *means* objectives explicitly stated. A total of 49 objectives were initially identified from the review of the EP documents. This process, detailed in Table E- 2 of Appendix E, led to a list of *fundamental* objectives that fall into themes identified here as Social, Economic, and Environmental. These were either Energy sector specific or Non-energy sector specific. These objectives, filtered down to a set of 13 *fundamental* objectives, explicitly (E) or implicitly (I) stated, and one category for Unclear Objectives are presented in Table 2-3. A total of 46 *fundamental* objectives are presented here as documents implicitly or explicitly repeated the same objective, while in other cases stated objectives implicitly referred to multiple *fundamental* objectives.

In Table 2-3 it is seen that the most commonly stated EP objectives were to increase access to modern energy (S1), to increase security of energy supply (EC1), to increase system reliability (EC2), and to minimize environmental impacts attributed to the energy sector (EN1). Economic objectives both within the energy sector and the non-energy sector were the most common with 18 references to economic objectives in the documents. Social objectives were the second most commonly stated with 15. Thirteen environmentally themed objectives were stated.

Nine of the *fundamental* objectives identified for this work were explicitly stated and the remaining 34 were implicitly referred to in the EP documents.

Table 2-3 - Fundamental Objectives

Theme	Objective	Code	Document D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	Count
Energy Sector																		
Social	Increase access to modern energy	S1		I	I						I	E		I	I			6
	Improve governance of the energy sector	S2		E							E	E						3
	Improve ability to provide affordable energy	S3				E								I			E	3
Econ.	Increase security of energy supply	Ec1	I	I							I		I		I	I		6
	Increase system reliability	Ec2		I	I	E			I	I		E					I	7
Environ.	Minimize environmental impacts attributed to the energy sector	En1	I	I		I					I	E			I	I	I	8
	Minimize adverse health impacts attributed to the energy sector	En2									I	E			I			3
	Minimize climate change impacts attributed to the energy sector	En3						I										1
Non-Energy Sector																		
Social	Improve quality of life of populations	S4	I												I			2
	Decrease rural emigration	S5													I			1
Econ	Increase economic development	Ec3	E	I											E		I	4
	Increase economic integration of West African States	Ec4		I														1
Unclear	Document with unclear objective	Un					•											1

E – Explicitly stated. I – Implicitly referred to.

It could be of some surprise that there appears to be little reference to objectives related to costs of investment, operation or maintenance. While cost-related objectives were not explicitly or implicitly referred to in the documents as part of their EP objectives, there were some references to cost attributes, despite not being clearly linked to objectives of "minimizing costs." The socially themed objective, S3 ("improve ability to provide affordable of energy") that references the costs of energy for end users was stated in 3 of the documents (D4, D12, and D15).

The use of objectives falling into different theme types was also examined. Of the 15 documents reviewed, 10 included more than one objective, and eight stated objectives falling into more than one theme type. Seven of the EP activities included objectives falling into all three themes of Social, Economic and Environmental objectives. The objectives of D5 were considered unclear.

What attributes are employed?

Attributes are quantifiable parameters used to assess the current state and to pre-assess the achievement of Objectives in various alternatives, and are important in ensuring that Objectives are linked into the actual EP process.

The Attributes found or inferred were disaggregated by their respective objective theme as well as the documents that consider them. Two types of Attributes were found in the documents; the first can be described as *diagnosis attributes* used to provide an understanding of a current situation or projection, but not used to compare alternatives for the future. The second type was *decision process attributes,* used in the process of comparing alternatives for the future. Of the initial list of 132 attributes, the most common attribute type was that of *diagnosis attributes*, with 79 counts, while the remaining 53 attributes were *decision process attributes*. It is of note that of the latter category, 27 were used within a single document, D6.

The initial list of 132 attributes was filtered down to a list of 63 attributes through a process of eliminating common attributes. This resulting list of attributes is presented in Table 2-4, together with the specific objectives to which they were determined to be linked to in the EP document as well as the documents in which they were used. The objectives are listed by the codes presented previously in Table 2-3.

Not all of the objectives could be clearly tied to an attribute used within the EP activity, namely objectives S2, S5, Ec3, & Ec4. Also, 11 attributes could not clearly be linked to an objective stated in the corresponding document. A number of the objectives were linked to multiple different attributes in different EP documents. The reverse was also found to be true, with attributes that were used for multiple different objectives.

What indicators are used for measurement and verification?

For this work, indicators are considered to be quantifiable parameters used to evaluate the outcomes of actions of the EP activity in relation to the achievement of the objectives set. Indicators provide a description of the energy system, and changes in their values over time provide information as to the progress, or opposite, in relation to the planning activities and the decisions made (Vera and Langlois, 2007).

None of the plans reviewed included any indicators with the specific purpose of monitoring or evaluation after plan implementation. Targets, however, 26 in total, were cited in the documents and used to state desired outcomes.

The targets could provide a starting point for the development of quantifiable indicators for the EP activities. Commonly the targets included a desired outcome, often cited in the form of a percentage of a total in a specified amount of time, or most often in a future year. Examples are “share of the population with access to energy [%]” (100% in D1), “share of population with coverage of electricity grid and/or natural gas cylinder sales network” (90% in D1), or “modern fuel adoption by households currently reliant on biomass for cooking” (50% in D3) or “renewable electricity generating capacity [MW]” (10.5% in D13). Yet these were not considered indicators as they were not presented with clear methods of quantification nor a plan for measurement and verification, but as an idealized target.

Table 2-4 – Attributes and objectives

	Attribute	Objectives								
		S1	S3	S4	Ec1	Ec2	En1	En2	En3	No Obj.
Themes ↓										
Social	Share of households with energy access by carrier	D2								
	Share of households with energy access by carrier from renewable sources	D2								
	National capacity for implementing the option								D6	
	Capacity for target groups to operate, maintain and eventually improve the new technologies								D6	
	Adequacy to meet national development objectives								D6	
	Electricity consumption per capita					D15				
	Number of electricity customers					D15				
	Share of population in location with electricity					D15				
	Annual trend of PES per capita				D11					
	Annual trend of electricity supply per capita				D11					
	Share of public kitchens with improved cookstoves				D2					
	Share of public kitchens with solar hot water heaters (hotels, restaurants, institutions)				D2					
Econ.	Cost for avoided CO_2 emissions								D6	
	Investment Cost (levelized and per unit of energy)			D4	D11, 14	D12			D6	D3, 9, 15
	Cost of electrical energy generation (includes over project lifetime accounting for fuel cost fluctuations)			D4	D14					
	Economic internal rate of return			D4						
	Cost Benefit ratio			D4						
	Economic net present value			D4						
	Annual savings of conventional energy sources			D4						
	Impacts on other economic sectors								D6	
	Annual trend in marginal cost of electricity				D11					
	Average annual marginal electricity cost by area inside of each ECOWAS member state		D12							
	Fuel cost					D12				
	Number of direct jobs created for construction, operation, and maintenance				D14					
	Impact of mitigation options at macroeconomic level								D6	
	Environmental benefits at local or regional level								D6	
	Employment generation								D6	
	Net benefit (monetary)								D6	
	Average cost of sequestered carbon								D6	
	Total Operation, maintenance, and fuel costs				D11					
	Average annual electricity generation cost				D11					
	Change in annual cost of imported fuels				D14					
	Cost of land preparation for carbon sequestration								D6	
	Benefit of land exploitation for carbon sequestration								D6	
Envir.	CO2 emissions				D11		D1, 9, 14		D6	
	Use of manganese instead of ethanol in gasoline						D2			
	Sulfur content in gas oil (automobile diesel)						D2			
	Total sequestered carbon								D6	
Energy system specific	Ratio of import to domestic petroleum products				D2					
	Raito of import to export of petroleum products				D2					
	Ratio of stock of refined oil products to national demand	D2				D2				
	Ratio of stock of crude oil to national demand	D2				D2				
	Change in annual imported fuels				D14					
	Fuel shares in energy and electricity				D11		D2		D6	D1
	Annual and total fuel savings by fuel type								D6	
	Annual final energy demand by carrier, & by sector	D9			D11, 14	D8, 15		D9	D6	D1, 4
	Annual final energy consumption by carrier, & by sector					D12			D6	
	Energy intensity by sector and carrier	D2			D2					
	Annual diesel fuel demand									D4
	Fuel consumption per GDP in transports						D2			
	Annual power factor for the industry sector				D2					
	% of national energy mix from renewable sources				D2					
	Share of electricity generation by energy conversion type (generation capacity or energy generated)				D2, 11, 14	D12, 14				D4
	Annual installed peak electricity generation capacity					D8, 10, 15				
	Annual peak electrical energy demand					D8, 10, 12, 15				D13
	Surplus and/or deficit elec. generation capacity (MW)				D11	D8				
	Annual electrical energy generation					D8, 12				
	Surplus and/or deficit electricity generation (MWh)					D8				
	Electricity imports & exports (total & ratio to domestic)				D9	D12				D15
	Reliability of electricity supply system	D2				D2				
	Transmission lines installed					D15				
	Distribution lines installed medium & low voltage					D15				
	Availability of Local & Imported Components									D4

2.6.3 How is energy demand considered?

How is energy demand forecasted?

The energy demand forecast methods employed in the EP activities are presented in Table 2-5. While 5 of the documents followed a statistical method (Past-future use projection), D3 D7 D9 D10 and D15, the most common method employed was a bottom-up approach (End-use Approach), used either exclusively as in D2 D6 & D11, from Ghana, Senegal, and Ghana respectively, or within a hybrid method (Bottom-up & Top-Down) as was the case in D1 D4 & D5, from Cape Verde, The Gambia, and Nigeria respectively. A Top-Down approach (Economic approach) was used in 3 documents from D8 D12 & D14. The method used was unclear in D13, from Nigeria.

Table 2-5 – Document demand considerations and scope

Doc.	Energy Demand Forecast Method	Urban & Rural Modeling Separation	Document Planning Horizon (years)	Number of Scenarios Presented	Number of planning alternatives considered	Modeling tools cited[2]	GHG consequences quantified in forecast	Additional pollutant emissions consequences quantified in forecast
D1	Hybrid	Yes	9	2	1	-*	CO_2	-**
D2	Bottom-Up	Y	14	3	4	MESSAGE, LEAP, Integrated Resource Planning, RETScreen	CO_2, CH4, N_2O	NOx, SOx, Non CH_4 VOCs, Particulate Matter
D3	Statistical	Y	9	1	0	MAED, WAsP	-**	-
D4	Hybrid	Y	20	1	1	-	-	-
D5	Hybrid	No	30	4	0	LEAP, COMAP	-	-
D6	Bottom-Up	N	15	1	0	MAED	CO_2	-
D7	Statistical	N	15	1	0	Multiple Regression Time Series	-	-
D8	Top-Down	Y	11	2	0	-	-	-
D9	Statistical	Y	21	1	0	-	-	-
D10	Statistical	Y	5	1	0	-	-	-
D11	Bottom-Up	Y	25	1	3	MAED, MESSAGE[1]	-	-
D12	Top-Down	N	14	2	0	-	-	-
D13	Unclear	N	25	3	0	-	-	-
D14	Top-Down	N	11	3	3	SIMRES, PVSist, Wind Atlas Analysis and Application Program(WAsP), KAMM	CO_2	-
D15	Statistical	N	19	1	0	-	-	-

1. Corrected from the original version after communication with author. * "-" not cited ** "-" none

2. Modeling tool abbreviations for figure: MAED -Model for Analysis of Energy Demand - from the International Atomic Energy Agency (IAEA), LEAP -Long-range Energy Alternative Planning- from the Stockholm Environment Institute, WASP -Wien Automatic System Planning Package for electricity generation expansion planning - from the IAEA, MESSAGE -Model of Energy Supply Systems and their General Environmental Impacts - from the IAEA, SIMPACTS -Simplified Approach for Estimating Impacts of Electricity Generation – from the IAEA, SIMRES- Generational unit commitment scheduling model- Source UNKNOWN, PVSyst - Photovoltaic System Studies, Sizing and Simulation Software, RETSCREEN -Renewable-energy and Energy-efficient Technologies Clean Energy Project Analysis Software - from Natural Resources Canada, COMAP -Comprehensive Mitigation Analysis Process for forestry, IRP -Integrated Resource Planning, WAsP- the Wind Atlas Analysis and Application Program, KAMM- Karlsruhe Atmospheric Mesoscale Model

What factors are considered in the demand forecast?

The factors used within considerations in the energy demand forecasts are presented in Figure 2-9. The most common criteria was that of "population projection", which was employed in 12 of the EP documents. Following this criteria, gross domestic product projections as well as considerations of infrastructure development plans were the most common in the documents and were considered in 9 and 8 of the documents considered. The criteria of "demand forecasts from previous work" refers to forecasts previously presented in separate documents. The other criteria here includes consideration of tourism, with a count of beds, used in D1 for Cape Verde as well as survey results for biomass consumption in Benin, D3. The criteria considered for one document, D13 for Nigeria, was unclear.

The informal sectors make up a large part of the economic activities in developing countries, and in SSA the size of the informal sector was estimated to be more than 40% of the gross national product in 2003 (Schneider, 2002; Verick, 2006). Here the informal sector is considered to be unregistered companies, often run from homes (ICLS, 2002).[10] The informal sector was not explicitly considered in any of the documents reviewed.

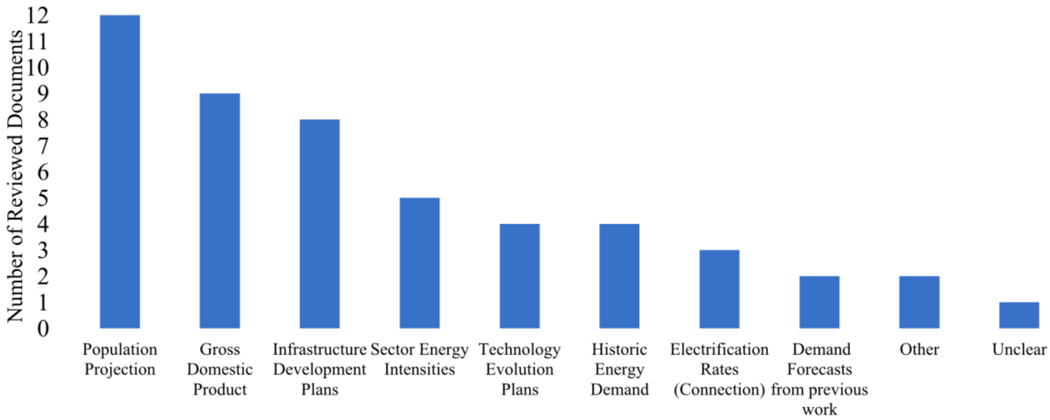

Figure 2-9 - Factors considered for energy demand forecast

Suppressed demand (i.e. needed energy services currently not supplied) is common due to budget constraints, resulting in less energy services demand in poorer areas, as well as the actual lack of infrastructure also not allowing demand to be met (Winkler and Thorne, 2002). Suppressed demand is important to consider, as looking solely at historic consumption overlooks this type of demand that may be manifested in the future if economic conditions improve. Suppressed demand for energy by populations was considered in the modeling of demand in 3 of the documents (D4, D8 and D12).

Are distinctions made between urban and rural energy demand?

Substantial differences exist between urban, rural, and peri-urban areas in developing countries. Populations in urban areas often have starkly different rates of access to modern energy services as opposed to rural and peri-urban areas. EP activities in developing countries should account for differences in these populations and areas.

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[10] Additional discussions of informal activities and definitions can be found in Garcia-Verdu (2007).

It was found that the demand modeling for urban and rural populations was done separately in eight of the 15 documents reviewed (Table 2-5).

How long are the planning horizons considered?

The planning horizons considered in the documents are presented in Table 2-5. Here the planning horizons are categorized within five year periods. Only D10, from Sierra Leone, had a short term planning horizon, 0-5 years. A medium term planning horizon was most common and 11 of the documents had horizons between 9 and 21 years. Longer planning horizons of 25 years or more were found in three documents.

How many scenarios are considered?

It is important to clearly delineate the terms used here to describe energy demand forecasting in the EP documents. *Forecasts* provide information about probable future situations often relying on past trends to provide a basis for extrapolation into the future. *Scenarios* then are those that are built upon factors that are not within the control of the modeler, but are quite relevant to future situations (Finnveden et al., 2003).

The economic development path of many developing areas is uncertain, requiring that EP activities take considerations for potential discontinuities in this development. The inclusion of multiple economic scenario forecasts allows for an understanding of energy demand within different development paths that may arise. Considering multiple scenarios is a way to deal with this uncertainty in future development paths, making for more robust EP (Bhattacharyya and Timilsina, 2010a).

The number of scenarios considered by the EP documents is presented in Table 2-5. Only one scenario is presented in eight of the 15 documents.

Where multiple scenarios are considered, they were constructed from variations of the economic development scenarios. As is the case in D1, for Cape Verde with two scenarios in which a moderated and an accelerated growth scenarios are used, as well as D5, for Nigeria, with four scenarios, a reference, a high and two optimistic economic growth scenarios are considered. Documents with two scenarios included D1, D8, and D12, and with three scenarios D2 and D13. As mentioned above, D5 was the only document with more than three scenarios.

All of the documents reviewed constructed scenarios for the purpose of forecasting energy demand, and so presented energy demand forecasts with the scenarios. It was, however, difficult to separate the two within the documents reviewed. In documents with only one scenario, there was not a discussion of the scenario followed by a description of the planning alternative considerations but actually a forecast of energy demand together with assumptions encapsulating both the scenario and the planning alternative. This means essentially that the scenario and the planning alternative were essentially considered as one and the same (while there could have been several alternatives within the same scenario – see next section).

How many planning alternatives are presented?

An *alternative* here is considered to be a hypothetical set of measures or policy interventions, that results in a future that reflects different outcomes as compared to the base-case. It is constructed over scenarios, which are not within the control of the modeler.

The number of documents that included planning alternatives is presented in Table 2-5.

Of the documents reviewed ten did not present any planning alternatives. Two documents, D1, for Cape Verde, and D4, for Gambia, presented one alternative based on implementation of DSM measures and renewable energy considerations respectively. D11, for Ghana, presented three alternatives, constructed from different policy options, for increasing the share of renewable energy options. D2, for Ghana, presented one alternative considering implementation of a DSM program, and three separate supply side alternatives considering different combinations of electricity generation technology options.

Are considerations of energy demand side management measures made?

One alternative to consider in the evolution of energy demand is the inclusion of DSM program measures. The scope of DSM activities has undergone a number of changes in recent years as a result of new communication technologies, technological advancements, and an understanding that DSM activities are not limited in scope to electrical utility planning but can include other energy considerations and planning activities (e.g. transportation fuels, other energy carriers, and urban planning). Suganthi and Samuel (2012) pointed out that DSM activities aid planning activities to: identify and prioritize opportunities for energy conservation; identify and prioritize energy resource use; frame policy decisions; and develop strategies for reduced environmental impacts.

DSM measures were considered and modeled in only two of the documents reviewed. D1 from Cape Verde presented an alternative considering DSM, referred to as rational energy use. D2, from Ghana, included a modeled alternative based on the application of a DSM program (Table 2-5).

2.6.4 What is the scope of the EP activity?

What modeling tools are used?

The modeling tools used in the documents reviewed are presented in Table 2-5. The modeling tools considered here are those that are cited as being used in the formulation of the document reviewed, and do not include tools used in works cited.

Of the documents reviewed two, D5 and D11, cited MAED (abbreviations are included with Table 5) from the International Atomic Energy Agency (IAEA). The Long-range LEAP from the Stockholm Environment Institute was employed in two of the documents, D2 and D6.

On the supply side, two documents, D5 and D11, cited the WASP from the IAEA, and one of the documents, D2, cited the MESSAGE from the IAEA. The package SIMRES (a generation unit commitment scheduling model) was cited in one document D14.

Tools used for renewable energy project analysis included RETSCREEN, as well as PVSyst. RETSCREEN was cited in one document from Ghana, D2, and PVSyst was cited in D14 from Cape Verde.

The COMAP tool was cited for use in modeling forestry concerns in one document, D6.

Two tools, considered methodologies but not software packages, are also presented. They included IRP, D2, applied in Ghana, and a multiple regression time series analysis, D7, used in Nigeria.

The wind resource modeling tools of WAsP, from the Risø National Laboratory in Denmark and KAMM were used in combination in D14 for local predictions of wind resources for power production from wind turbines and wind farms.

Which primary energy sources and energy carriers are considered?

PE sources are those that are extracted or taken straight from natural resources. Energy carriers, often referred to as final or secondary energy, are produced from PE sources or other energy carriers and are those that enter into the actual place of use (i.e. the household) (IEA, 2005).

The PE sources, shown in Figure 2-10, most commonly considered in the documents were from renewable sources. Wind was considered in nine documents, both Solar and Hydro in eight documents, and Biomass in seven documents. Gas was the most commonly considered fossil fuel energy source, stated in five documents. Imported electricity was cited in five documents, from countries located on the continent.

The secondary/FE carriers cited are shown in Figure 2-11. Electricity was considered in 12 of the documents. Biomass was the second most commonly considered of the carriers and was included in eight of the documents. Diesel fuel was considered in seven of the documents, and gas was cited in five of the documents. Kerosene, RFO, and gasoline were all cited in four of the documents.

Demand for traditional energy carriers remains the largest FE demand in the ECOWAS region, representing 80% of FE demand (UEMOA and ECOWAS, 2006). Biomass was considered in eight of the 15 documents as part of considerations for energy carriers.

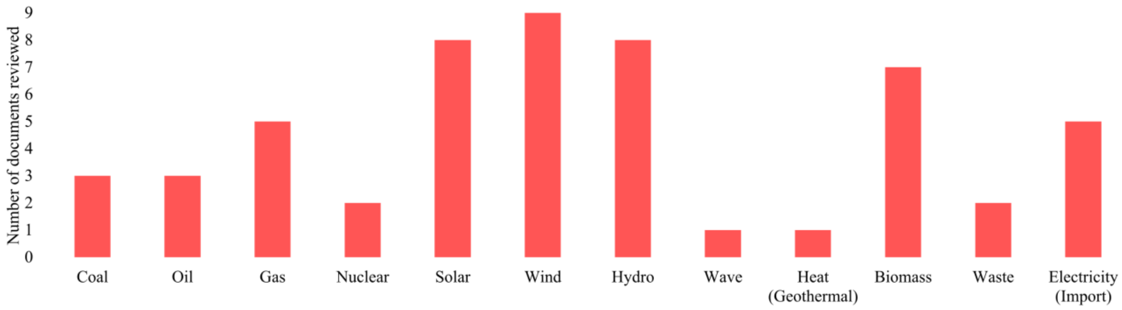

Figure 2-10 – PE sources considered – Number of documents that considered each PE source

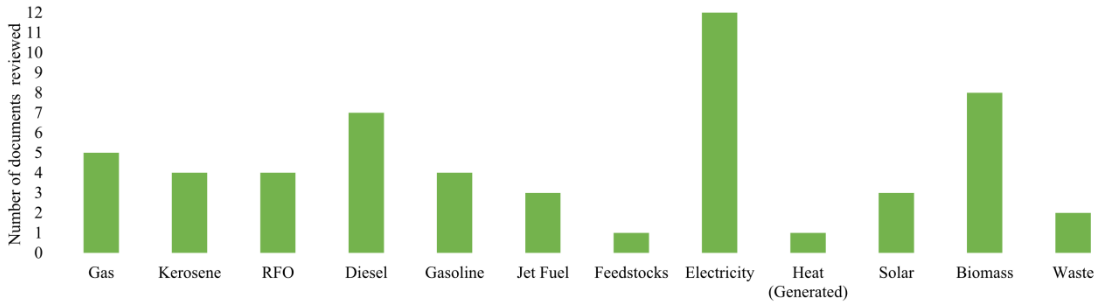

Figure 2-11 – FE carriers considered - Number of documents that considered each carrier

Are environmental consequences of energy use quantified?

Quantification of CO_2 emissions according to each future alternative, was found in four of the documents, D1 from Cape Verde, D2 from Ghana, D6 from Senegal, and D14 also from Cape Verde. Only one document, D2 from Ghana, included the quantification of specific additional GHGs, namely CH_4 and N_2O as well as four other pollutant emissions. Table 2-5 presents the number of documents that included the quantification of environmental ramifications due to energy demand.

2.6.5 What energy planning indicators are employed?

As part of this review of EP activities, a review of indicators used was conducted to establish an understanding of the level of specificity of EP indicators for the region and possibly developing countries in other regions.

The Environmental policy from the ECOWAS Commission (2008) requires states to carry out environmental studies or impact assessments on investments and actions with potential environmental impacts. Assessment activities that should run in conjunction to EP activities require quantifiable indicators that allow for measurement and verification activities. International aid organizations have included Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA) type requirements for lending and development programs (Chaker et al., 2006). While a number of sets of energy based indicators have been presented, there is not a consensus as to the level of specificity needed in indicators for different contexts of application, and especially in developing countries (EEA, 2005; Foster and Tre, 2000; IAEA, 2005; Kemmler and Spreng, 2007; Neves and Leal, 2010; Practical Action, 2012; Sheinbaum-Pardo et al., 2012; UN Economic Commission for Africa, 2009; Vera and Langlois, 2007; World Bank, 2013c). There have been no studies of indicators for specific application in the framework of EP activities of SSA or specifically ECOWAS members.

A number of energy based indicator sets have been presented recently. These include general sets of sustainable energy indicators from Vera and Langlois (2007), International Atomic Energy Agency (IAEA) (2005), and Patlitzianas et al. (2008). The EEA (2005) also presented indicators for use in more developed countries, within the context of the European Union. A set of energy based indicators, for local EP in more developed countries, was presented by Neves and Leal (2010). Kemmler and Spreng (2007) and Neves and Leal both presented sets of core or lead indicators as subsets of indicators meant to provide a dashboard analysis of important measures of the system in question for policy considerations. While these provide examples of indicators they may not always be complete sets that are expressly applicable to the context of developing countries.

Indicators describing a country's transition to modern energy, measuring energy poverty indicators were explored by Kemmler and Spreng (2007). The sets for measuring the impacts of energy reforms for the specific countries of Mexico and of Guatemala, developing nations of Central America, have been established by Sheinbaum-Pardo, Ruiz-Mendoza (2012) and Foster and Tre (Foster and Tre, 2000) respectively. The World Bank presents an annual review of African Development through a large set of African Development Indicators that detail some parts of the energy sector (World Bank, 2013c). The UN presented a preliminary set of general sustainable development indicators for African countries (UN Economic Commission for Africa, 2009). The Poor People's Energy Outlook presented indicators more specific to the energy sector in developing countries and made considerations for energy's importance for earning a living and the importance of energy at the household level (Practical Action, 2012).

Two sets of energy sustainability indicators for local EP for use in developed countries, presented by Neves and Leal (2010) were used as part of this work for juxtaposition with indicators used within the ECOWAS region. The first set consisted of 59 energy based indicators, resulting from a literature review of sustainability indicators. The second set resulted from a methodology of refinement of the first set to a revised set of 18 state and policy energy based indicators for local EP.

Monitoring and evaluation intentions were absent at the EP stage of the documents reviewed. In the EP documents recovered for this work, as discussed previously, no indicators for monitoring plans were found. With the EP documents reviewed for this work, any measure of impact of the plan against a "no plan" future would not be possible without indicators and monitoring plans. It must be noted that one document, D2 from Ghana, stated that SEA activities would be completed with the plan, however no SEA or monitoring plan was provided together with the plan. The Ghanaian Environmental Protection Agency (EPA) requires SEA activities to be completed with energy sector projects of this scale (EPA Ghana, 1999).

Less than 50% of the indicators presented by Neves and Leal (2010) as energy based sustainability indicators were employed in the ECOWAS member states documents, and only three of these indicators were commonly cited in the documents. These included indicators pertaining to renewable energy shares, annual energy consumptions, and GHG emissions. Within the second more refined list of local energy based sustainability indicators proposed by Neves and Leal, only indicators for renewable energy share, and GHG emissions were widely employed in the documents reviewed. This comparison is not presented in table form here, as the indicators are also present in the first list, however the results are discussed.

Few similarities were found between the attributes in the documents reviewed and the indicators employed or recommended for use in planning activities of developed countries. This may represent a specificity of these indicators to developed countries, but it also may represent a gap in the planning activities of the region. Of course the specificity of the indicators can be assessed from the other side to evaluate those used in the ECOWAS member states but not in the list presented from Neves and Leal, and attributes such as new connections to the electric grid, trend in marginal costs of electricity, capacity to maintain and operate new technologies attest to the specificity of attributes and indicators to regional objectives. As the plans reviewed lacked indicators for monitoring and evaluation, there is still some development needed in the planning activities in order to ensure that they employ metrics and procedures that link objectives from the plan formulation through to assessment activities.

The specificity of the indicators should also be assessed, from the other side, to evaluate those used in the ECOWAS member states but not in the list presented from Neves and Leal, and attributes such as new connections to the grid, trend in marginal costs of electricity, capacity to maintain and operate new technologies attest to the specificity of attributes to regional objectives.

Documents 1 and 2, from Cape Verde and Ghana respectively, both employed the largest number of indicators on the list. They are also the two ECOWAS member states classified as Medium Human Development by the UNDP.

2.7 Updated review of EP activities - 2015

An additional literature review of EP activities in the ECOWAS region was conducted at the final stage of this thesis to bolster the initial review and ensure that the literature review included relevant recent activities. The updated review of literature was conducted in the period of May to June in 2015.

2.7.1 Methodology

Document discovery

An online search was undertaken to identify and collect EP documents at the national level of the individual ECOWAS members as well as the ECOWAS region from sources consisting of governments, government institutions, international organizations, and academic research journals. After searching these sources and following references cited in the works recovered, a point was reached when no additional documents were identified.

This collection process identified 41 potential EP documents that are listed in Table E- 3 of Appendix E. From this set, Energy Policy and Program Specific documents were eliminated and only EP documents, as defined in the previous Section 2.5.1, were considered for the analysis. The filtration process is presented below in Figure 2-12. This resulted in a total of 15 supplementary EP documents presented in the results that follow. These supplementary documents are reviewed separately from those presented in the previous literature review above.

Because an online document search has limitations as not all EP documents are available online from actors in the ECOWAS region, in the first literature review, described above in Section 2.5, a survey of EP actors in the region was conducted to discover additional documents, to potentially overcome these limitations. However, that survey had a low response rate and produced only one additional document to add to the initial list of 14 documents. Therefore, this updated review for 2015 the additional survey procedure was deemed not necessary.

Matrix of analysis

To maintain consistency in the results the systematic review of the documents followed the four main questions detailed in the matrix of analysis from the previous work shown in Table 2-2.

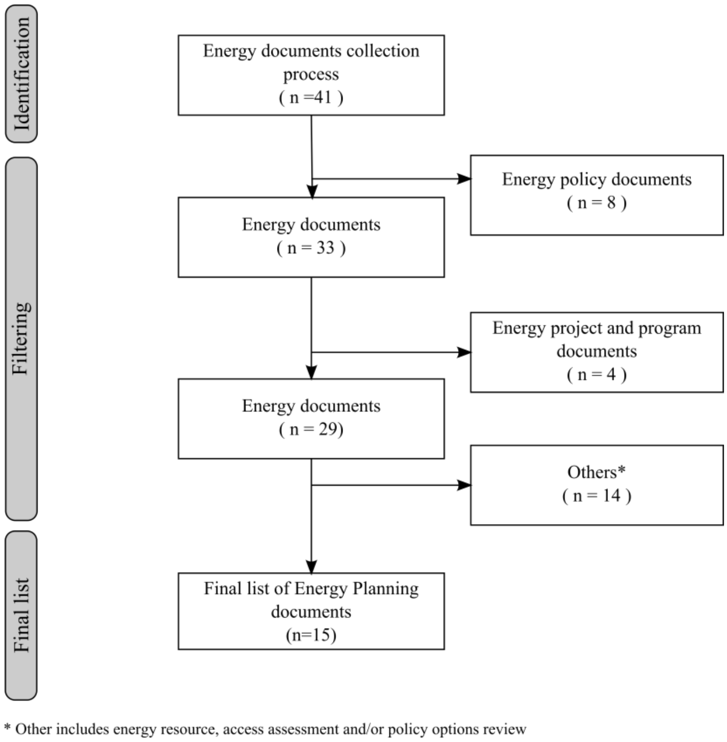

Figure 2-12 - Flowchart of Supplementary EP document literature review

2.7.2 Results

Who is active?

The 15 supplementary EP documents identified in the updated review of EP activities in the ECOWAS region are presented in Table 2-6. The documents represent EP activities conducted by six ECOWAS members. The members identified as active in EP in this updated review were all active in the previous review presented in Table 2-1.

Multiple works were completed for the national level EP activity in Cape Verde and Nigeria. Two of the works from Cape Verde were articles presenting research from third party research groups. EP documents for Nigeria consisted of three reports published by government ministries as well as three research articles. Reports from government entities were identified for Benin, Gambia, and Liberia.

A research article for SSA was identified that also includes a less aggregated analysis of the West African region. A revised plan for the WAPP was also identified.

What is the purpose of the EP activity?

The majority of the EP activities, 12 of 15 documents, are concentrated on electric system planning as was also true in the previous review.

One environmental protection plan that included an energy systems model for Cape Verde for a study on impact on global climate was found. Two documents were identified as masterplans. One was specific to the industrial sector, however included multiple sub-sectors and FE carriers. A second document studied the inclusion of hydrogen as a FE carrier in the transportation sector, however included multiple FE carrier demand in analysis of EP alternatives.

Table 2-6 – Supplementary EP documents and type

Doc.	Country	Document Name	References	Document Type- **R**eport or **A**rticle			
				Energy Master Plan	Electric System Plan	Env. Protection Plan	Basic Energy Services Plan
S1	Benin	Strategic development plan for the energy sector of Benin	(DGE - MEE, 2009)		R		
S2	Cape Verde	Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde	(Segurado et al., 2011)		A		
S3	Cape Verde	Development of energy projections: CLIMA-IMPACTO project (MAC/3/C159).	(Factor CO2, 2012)			R	
S4	Cape Verde	Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde	(Segurado et al., 2015)		A		
S5	Gambia	Electricity strategy and action plan	(AF-MERCADOS EMI, 2012)		R		
S6	Liberia	Options for the development of Liberia's energy sector	(World Bank, 2011b)		R		
S7	Nigeria	An energy system planning model for the industrial sector in Nigeria	(Njoku, 2008)	A[1]			
S8	Nigeria	More for less: How decentralized energy can deliver cleaner, cheaper and more efficient energy in Nigeria	(WADE et al., 2009)		R		
S9	Nigeria	Renewable energy masterplan: Revised draft	(ECN and FMST, 2014a)		R[2]		
S10	Nigeria	Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications	(Aliyu et al., 2013)		A		
S11	Nigeria	Draft national energy masterplan (NEMP)	(ECN and FMST, 2014b)		R[3]		
S12	Nigeria	An integrated impact assessment of hydrogen as a future energy carrier in Nigeria's transportation, energy and power sectors	(Amoo and Fagbenle, 2014)	A			
S13	Senegal	Modeling the transition towards a sustainable energy production in developing nations	(Thiam et al., 2012)		A		
S14	SSA	Energy access scenarios to 2030 for the power sector in sub-Saharan Africa	(Bazilian et al., 2012)		A		
S15	WAPP[4]	West African Power Pool: Planning and Prospects for Renewable Energy	(IRENA, 2013a)		R		

R- Report
A- Journal Article

1. Considered energy master plan specific to the industrial sector as multiple sub-sectors and FE carriers are included in the work.

2, 3. Despite "masterplan" title forecasts are limited to the electricity sector, although some projections for fossil fuels demand are included. All other values are targets.

4. West African Power Pool (WAPP)

The focus on electricity system planning echoes the findings from the previous review and the concentration of increasing access to electricity in the region. Energy master planning continues to be less common, and in the current update no masterplans for the national level including PES considerations together with multiple FE demand sectors and multiple FE carriers were found.

The fundamental objectives cited either explicitly (E) or implicitly (I) in the respective EP documents are presented in Table 2-7.

Within the energy sector specific objectives the most commonly cited socially themed objective was to maximize access to modern energy (S1) (note: document labels refer to Table 2-6). The same objective was the most cited in the previous review. Minimizing costs of FE for the population (S2) was also cited in 3 of the documents.

Maximizing PE security (Ec1), as in the previous work, was the most commonly cited economic (Econ.) objective. 13 of the 15 documents cited this objective; however this was most often implicitly cited by stating maximizing renewables in the PES and FE carriers.

Minimizing the impact on the global climate was the most commonly cited environmental (Env.) objective. The majority of these citations were considered implicitly cited. This objective was not the most commonly cited environmental objective in the previous review and was only cited in a single document, while impact on the local environment was the most common. Minimizing energy sector impacts on the local environment was the second most commonly cited objective under this theme in this updated review, cited in 6 of the 15 documents.

It is of note here that clear explicit declaration of the objectives for the undertaken EP activities was not common. Of the 52 objectives identified in the 15 documents, only 15 were explicitly stated, while 37 were implicitly referred to by a means objective that was not clearly defined.

How is energy demand considered?

The energy demand considerations from the updated review are presented in Table 2-8.

The energy demand forecast was nearly evenly divided between Top-down (economic), bottom-up (end-use) and statistical (past-future use projection) approaches with 5, 6 and 4 of the documents citing each approach respectively.

Three of the 15 documents made specific separation of rural and urban populations in modeling FE demand.

The document planning horizons were predominantly medium-term from 10 to 25 years, 12 of 15 documents. The strategic development plan from Benin, S1, was the only short-term plan. The plan for hydrogen integration in the transportation sector of Nigeria, S12, assumed that the emerging technology and FE carrier was expected to require a long-term horizon for modeling. The electricity system plan from Liberia, S6, also had a long-term 30 year horizon.

As in the previous review, the EP activities fused the concepts of scenarios and alternatives together, resulting in some difficulty in ascertaining considerations of the future scenario and considerations for the alternatives considered as defined previously. This results in a loss of useful tools, in addition to clarity, in the modeling of alternatives.

Table 2-7 - Supplementary documents - fundamental objectives

Theme	Objectives Stated	Code	Supplementary Documents (S)															
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	Count
Energy sector																		
Social	Maximize access to modern energy	S1	I					E			E		I			I		5
	Minimize costs of FE for population	S2	E				I			I								3
	Maximize local capacity in renewable energy systems	S3									E		I					2
	Strengthen national capacities for energy sector planning and management	S4	E															1
	Improving the legislative and regulatory framework of the energy sector	S5	E															1
	Minimize total cost (end-use technologies)	S6												I				1
Econ.	Maximize PE security	Ec1	E	I	E	I	I		I	I	E	I	I	I	I		I	13
	Maximize economic growth	Ec2									E		I	I				3
	Minimize total cost (Inv. Oper. & Maint. of conversion technologies)	Ec3						E		I				I				3
	Reliability of FE supply	Ec4	I				I		I									3
	Minimize the total annual cost of electricity and water(desalinization) production	Ec5				E												1
Env.	Minimize influence of the energy system on global climate	En1			E		I			I	I	I		I	I		I	8
	Minimize influence of the energy system on the local environment	En2	I							I	E		I	I	I			6
Non-Energy sector																		
Social	Increase the scope and quality of government services	S7									E		I					2

E – Explicitly stated I – Implicitly referred to.

Eight of the 15 documents, cited only one future scenario within which alternatives were considered. Seven of the documents cited additional scenarios based on possible future economic development paths.

In five of the 15 EP activities the scenario was fused together with the FE demand projections and no planning alternatives were constructed. Nine of the documents cited multiple EP alternatives. Two of these included considerations of DSM interventions.

While three of the modeling tools used in the documents reviewed were identified in the previous review, seven additional modeling tools, seen in bold in Table 2-8, not previously seen employed (main literature review results presented above Section 2.6) in the ECOWAS region were identified.

What is the scope of the EP activity?

The EP tools, which were previously generic in their area of applicability, were found to now have increased specificity in their context of application (Table 2-8). Tools such as SPLAT-W were developed specifically for modeling activities in West Africa by The International

Renewable Energy Agency (IRENA). The model applied in S2 and S4 was employed in Cape Verde and developed especially for EP of islands and isolated regions. The model used in S3, CaVE, was developed specifically for the planning activity and evaluation of impact on the global climate in the country of Cape Verde.

Seven of the documents included a quantified forecast of GHG emissions. This attribute was used in evaluation of EP alternatives where they were considered. It is of interest though, that eight EP documents included, implicitly or explicitly, an objective of minimizing the impact on the global climate.

Three of the documents included additional quantified forecasts of pollutants as attributes of impact on the local environment. NO_x and SO_x were the most common pollutants quantified, however volatile organic compounds (VOCs) and particulate matter were also considered in S12 and S8 respectively. While three documents included this quantification, six documents cited, implicitly or explicitly, an objective of minimizing the impact on the local environment.

Considerations were not made in the majority of the documents for the PE requirements in the “business as usual” projection or in the constructed EP alternatives (Figure 2-13). While three documents S2, S3 and S4 considered the renewable resource of wind for electricity generation, only a single document S12 quantified the PES requirements of fossil fuel, coal, oil, gas, and other combustion fuels, biomass and waste.

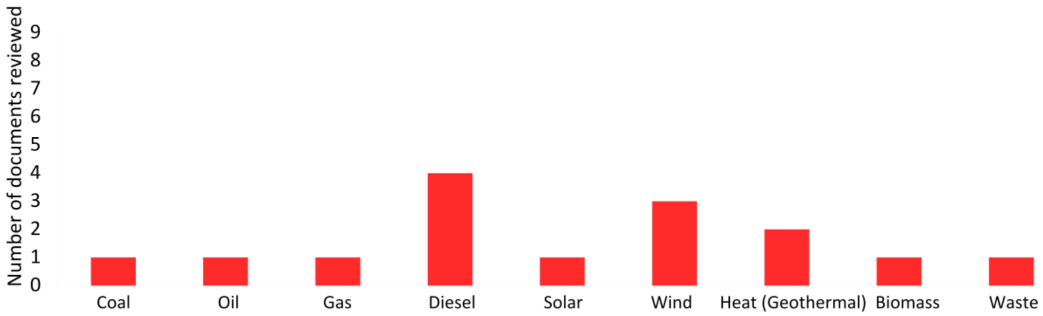

Figure 2-13 – PE source considered in supplementary documents – Number of documents that considered each PE source

Electricity was the most commonly FE carrrier considered and FE demand was forecast in all of the EP documents reviewed (Figure 2-14). This result is in line with the previous review and reflects the concerted efforts by actors in the region to increase electricity access rates in the region. Although biomass provides for the majority of FE demand in the residential, services and industrial sectors it was not quantified in FE demand forecasts reflecting the previously cited concentration on electrical energy systems by governments (ESD et al., 2007).

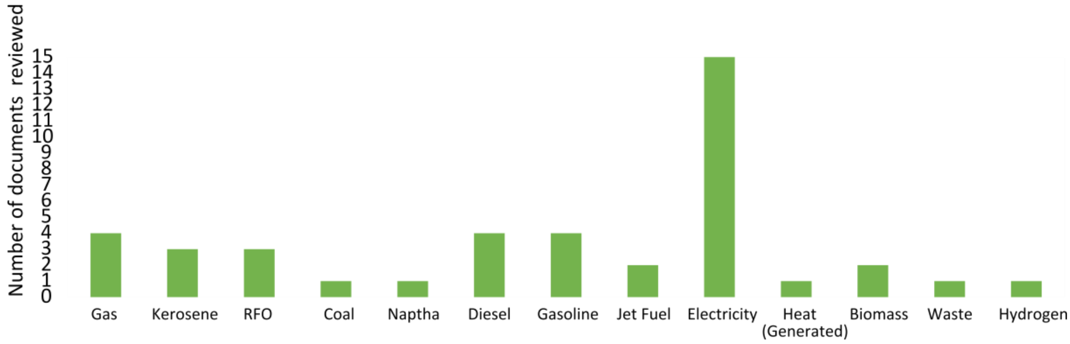

Figure 2-14 - FE carriers considered in the supplementary documents - Number of documents that considered each carrier

Table 2-8 – Supplementary documents - demand considerations and scope

Doc.	Energy Demand Forecast Method[*]	Urban & Rural Modeling Separation	Document Planning Horizon [years]	Number of Scenarios Presented	Number of planning alternatives considered	DSM measures modeled?	Modeling tools[1]	GHG consequences quantified in forecast	Additional pollutant emissions consequences quantified in forecast
S1	-	**N**o	6	1	0	**N**o	-[b]	-	-
S2	Top-Down	**N**o	25	1	4	**N**o	**H_2RES**	CO_2	-
S3	Statistical & Bottom-up[2]	**N**o	13	2	1	**N**o	**CaVE**	CO_2	-
S4	Top-Down	**N**o	10	1	4	**N**o	**H_2RES**	CO_2	-
S5	Top-Down	**Y**es	20	1	7	**N**o	-	CO_2	-
S6	Top-Down	**Y**es	30	2	2	**N**o	**GAMS**	-	-
S7	Statistical	**N**o	10	3	0	**Y**es	-	-	-
S8	Statistical	**N**o	20	1	5	**Y**es	**WADE**	CO_2	NO_x, SO_2, PM_{10}
S9	Bottom-up	**N**o	20	3	0	**N**o	MAED & MESSAGE	-	-
S10	Bottom-up[3]	**N**o	20	4	0	**N**o	-	CO_2	-
S11	Bottom-up	**N**o	20	3	0	**N**o	MAED & MESSAGE	-	-
S12	Bottom-up	**N**o	40	1	3	**N**o	LEAP	CO_2	NO_x, SO_2, N_2O, VOCs
S13	Top-Down	**N**o	24	3	3	**N**o	**PowerPlan**	-	NO_x, SO_2
S14	Statistical[4]	**N**o	20	1	4	**N**o	**OSeMOSYS[5]**	-	-
S15	Bottom-up	**Y**es	20	1	3	**N**o	**SPLAT-W**	-	-

* "-" not cited ** "-" none

1- H2RES -Energy planning of islands and isolated regions (Instituto Superior Técnico, University of Zagreb., n.d.); CaVE- Cabo Verde Modelo Energético (Factor CO2, n.d.); GAMS- General Algebraic Modeling System (GAMS Development Corporation, n.d.); WADE-World Alliance for Decentralized Energy: Economic model. (The World Alliance for Decentralized Energy, 2015); PowerPlan -an interactive simulation electric power planning model (de Vries and Benders, 1994); OSeMOSYS- Open Source Energy Modelling System (Howells et al., 2011); SPLAT-W. System Planning Tool (West African Power Pool system) (IRENA, 2015).

2- The reference scenarios were based on a past-future projection. A bottom-up method was used in construction of the alternative projection.

3- Demand forecast is from external source. The current table refers to the method in this external source. See reference in article.

4- Demand is forecast based on assumed energy intensity [kWh/capita], population, and access levels.

5- Used in the analysis of a single constructed alternative.

2.8 Summary of literature review

The application of a matrix of analysis to a comprehensive set of energy plans provided a characterization of the EP activities within the ECOWAS region, with the aim of establishing an understanding of current EP practices in the region. The results of the updated review of EP activities were mainly consistent with those of the main review. The summary presents an analysis applicable to the finding of the two review processes.

The summary is presented in a question-driven format including recommendations for each topic analyzed. Implications are presented to drive the development of an EP methodology for the current work. Recommendations that may also aid in future effective EP activities are highlighted as well.

2.8.1 Who is active in EP activities?

EP documents conforming to the requirements of this review (i.e. having a quantified demand forecast) were discovered for 10 of the 15 ECOWAS members and the WAPP in the main review. Only 6 of the 15 ECOWAS members and the WAPP were represented in the updated review. The ECOWAS members with EP documents are the same in both the first literature review and the updated literature review and no documents were identified for countries absent from the first literature review. Benin, Cape Verde, Gambia, Liberia and Nigeria and the WAPP were identified to have EP documents in the main review and additionally in the supplementary review. Cape Verde with five documents and Nigeria with nine documents were the ECOWAS members with the most EP documents identified in the two reviews. In the updated literature review an additional EP document for the whole SSA region was also identified.

Both local and foreign contributions were found in the EP activities, with common collaboration between local and foreign actors. Initiative for the planning activity and management was predominantly provided by local government ministries and agencies. Local technical effort was also seen from government ministries and agencies as well. Foreign technical effort from international organizations and consultants was common throughout the documents.

EP approaches need to promote stakeholder engagement in the EP activity. This would provide mechanisms to connect energy policy and planning decisions to the actors responsible for actual implementation.

Implications:

- EP frameworks should allow for broad stakeholder engagement in the planning process through group decision processes. Such group decision processes may be supported by MCDA tools as a means to facilitate taking into consideration the objectives of all stakeholders. This will allow for connections between and ownership for the various actors involved both in policy and planning and those charged with actual implementation.

2.8.2 What is the purpose of the EP activities?

All of the EP documents recovered were for national EP purposes. EP documents with quantified demand forecasts on the local scale as well as for rural areas were not found either through the internet search or through the inquiry of ECREEE NFI contacts, most probably implying that they do not exist. The perceived absence of EP activities at these scales, below the national level, is of importance as, for example, populations in rural areas commonly have less access to modern energy services than urban populations.

Electrical system planning documents were the most common type, representing 9 of the 15 documents recovered. Energy master planning documents considering a wider range of energy carriers were less common representing 3 of the 15 documents recovered. Energy demand is forecasted primarily for power sector considerations. Additional considerations of FE demand for biomass, gas, heat, gasoline, and diesel fuel were not as common as considerations of electricity. Electrical energy systems planning was the most common, and energy master planning activities remain nascent in the region.

The PES requirements are largely overlooked in forecasts for these FE demands. This absence makes quantification and evaluation of future PE security considerations, a commonly cited EP objective of the region, difficult if not impossible.

Energy master planning allows for the consideration of multiple energy carriers in addition to electricity and allows for the matching of energy demands with different carriers. It also permits actors to evaluate the carrier that may be most suited for particular demands given specific circumstances. Considering multiple energy carriers may also allow actors to consider alternatives where PE supplies and FE carriers are more diversified.

Cited objectives were predominantly economically themed. The most commonly cited objectives within the social, economic and environmental themes were to increase access to modern energy, to increase security of energy supply, increase system reliability, and to minimize environmental impacts attributed to the energy sector.

The fundamental objectives for the EP activities were not explicitly stated in some of the EP documents reviewed, but were often implied through means objectives. Also, disconnections were found between the objectives set for the EP activity and attributes employed to pre-assess the achievement of these objectives. There were a number of objectives set in the EP process that could not be clearly linked to attributes in the planning process. The reverse was also found: a number of attributes were employed but could not be specifically linked to an objective. Also, EP objectives could be linked to a wide array of different attributes, as well as attributes being linked to multiple different objectives. Attributes were also found to be most often used in a diagnosis capacity rather than used in the decision making processes of analyzing alternatives.

No indicators for future monitoring and evaluation activities explicitly referred to as such, were found in the EP documents. However, there were EP documents that cited loosely defined targets as desired outcomes. Without monitoring and evaluation, the outcomes and effectiveness of these EP activities cannot be assessed, and no corrective measures can be adopted in due time. There may also be a financial side here, which means that governments or agencies involved will not know how effectively funds and budgets for EP will actually be applied.

There are, currently available in the literature, examples of both attributes and indicators for most of the objectives found in the EP documents reviewed (IAEA, 2005). For example the objective "To improve ability to provide affordable energy" (Sc3) could probably be appropriately translated through the indicator "share of household income spent on fuel" and "electricity and household energy use for each income group and corresponding fuel mix" (Foster and Tre, 2000; IAEA, 2005).

Implications:

- The EP framework should follow an energy master planning approach, as this would allow for the inclusion of additional energy carriers (e.g. natural gas, generated heat, biomass, solar, for photovoltaic and water heating, etc.), which may lead to systemic gains.
- The use of the EP activity for promotion of a specific technology, in this sense, should be avoided, but instead used to consider multiple energy carriers, which can provide for energy services through a variety of energy transformation technologies (World Bank and UNDP, 2005).

Globally, from the analysis of objectives, attributes and indicators of EP processes in the ECOWAS region, there seems to be a need for more structured planning practices, which enable initiative and process management actors to better design the plans.

Implications:

- Identify fundamental objectives as these provide the foundation for decision processes, explain the overarching reasons for which the EP activity is undertaken, and establish structure in the EP activity (Keeney and Gregory, 2004).
- Ensure that these objectives are applicable to the geographical context, and that they include concerns that value alternatives that are implementable.

- Translate objectives into attributes as part of a structured decision-making process, ensuring that decision alternatives are created and that the choice among them considers their potential to fulfill the stated EP objectives.

2.8.3 How is energy demand considered?

The energy demand forecasting methods described, in the documents where it was addressed, consisted most commonly of statistical (past to future) projections. However bottom-up methodologies, either solely bottom-up or within hybrid methods, were also common.

An interesting observation was that energy demand considered suppressed or unmet was included in the modeling of demand in three of the 15 documents. As many areas have not had the physical access or financial ability to access modern energy services, a simple projection of historic growth of consumption data may leave out the demands that these populations represent. Also documents did not specify if the informal sector was considered in energy demand forecasts. This may be problematic given the energy demand that can be undoubtedly attributed to informal activities as they constitute a large percentage of the economic activity within these countries.

Bottom-up or hybrid methodologies allow for planners to start from the energy services that end-users actually demand and to include demands that may be overlooked in statistical projections. Also with a starting from the end-user energy services with a bottom-up method allows for considerations of multiple energy carriers in meeting different demands and is conducive to master planning activities.

The EP horizons are predominantly medium term, and 11 of the documents had horizons between 9 and 21 years.

The criteria used in the forecasting methods were primarily considerations of population projections, GDP projections, and infrastructure development plans. Criteria such as historic trends of energy demand were also employed.

Distinctions were made for urban and rural populations in eight of the documents reviewed; peri-urban populations were not discussed in the documents.

The majority of the documents, eight of 15, consider only a single scenario, as defined previously in Section 2.6.3, within the discussion of the number of scenarios considered. When multiple future scenarios are presented, these are based on different economic growth scenarios.

The line between the scenario, planning alternatives, and demand and PES forecasts was not clear in the majority of the documents reviewed, and the scenario and energy demand forecasts were one and the same. Also, planning alternatives representing different policy initiatives, for example, were absent in ten of the documents reviewed. The modeling of a single scenario for the future deprived actors of the potent ability to model multiple policy interventions within EP alternatives. The absence of alternative future scenarios and the consideration of planning alternatives affect the robustness of the planning process.

Implications:

- Ensure that the EP methodology employed is suited to the context of the application. As suppressed/unmet demand, as well as informal sector demand, are mostly absent from historical data, a statistical (past to future) projection may be inadequate in forecasting energy demand.
- Include considerations of rural, urban and peri-urban populations in national level planning or local city or municipal planning efforts as urban populations in the region are projected to grow in the near future (Fall et al., 2008).
- Consider multiple possible scenarios to improve robustness as the future is uncertain and a single future scenario provides little information for other possible futures. These can include economic growth scenarios as well as others.
- Develop multiple constructed alternatives in EP activities of the region to allow for the evaluation and comparison of different policy measures to be considered in their achievement of stated objectives. The assumptions for these alternatives and their evaluation, with attributes, should be clearly presented and compared in the EP document. This allows for transparency in the methodology but also presents the policy makers and public with information that allows for construction of appropriate energy policies to achieve objectives.

2.8.4 What is the scope and what are the tools being adopted?

The tools used within the EP activity were diverse, from international sources and common to those used within developed countries. These tools include energy demand and supply side models such as LEAP, renewable energy project analysis including RETScreen, and biomass supply models. Not all of the EP documents reviewed cited the modeling tool employed.

Renewable energy supplies were the most common PE sources considered, including solar, wind, hydro and biomass sources. The next most commonly considered was natural gas. This may reflect the development of the West African Gas Pipeline (WAGP), which would increase the availability of gas in ECOWAS members with connections. Electricity imports were also considered in numerous documents reflecting the development of the WAPP and the interconnections that this allows and will allow. As concerns of increased energy security and decreased environmental impacts were expressed in the EP objectives cited in the documents it is important for countries in the region to not only consider a shift to renewable energy supplies, but also options such as diversification of PE resources.

EP activities within ECOWAS will have to consider recent regional energy market developments. The completion of a WAPP will allow for the import and export of electrical energy between the member states. Also, the construction of the WAGP will permit natural gas exchanges between member states. These efforts will aid in establishing energy markets for the community, composed of states with diverse PE resources (GTZ, 2009).

Electricity was the most commonly cited energy carrier. Other carriers (e.g. diesel and natural gas) are also considered, but as electricity systems plans were the most common, electricity was also the most common carrier considered. This also reflects objectives set in the region, not only for access to modern energy, but specifically for increased access to electricity (UEMOA and ECOWAS, 2006). Consideration of traditional energy (e.g. biomass or woodfuel) was found in eight of the documents.

The environmental ramifications of the alternatives presented in the EP activity were not considered in the majority of the documents. However, four documents included forecasts of CO_2 emissions and of these, one (D2 from Ghana) considered other GHG and additional pollutant emissions.

Implications:

- Include considerations of PE supplies and their sources, including fossil fuels (e.g. oil & natural gas) and not solely a shift towards renewables as part of energy security considerations.
- Include considerations of multiple FE carriers in master planning efforts, and allow for the consideration of multiple carriers in meeting the demands of end-users for energy services. Energy demand for cooking, an energy service, can be met by electricity (grid or solar photovoltaic), natural gas (grid or bottle), or direct solar for example.
- Include a consideration of the environmental ramifications when modeling and forecasting alternatives to better allow for the evaluation of these alternatives in their fulfillment of objectives to minimize the environmental impact of energy systems.

2.8.5 Specificities of EP activities

While improving access to modern energy services may represent a specific objective to the realities of ECOWAS countries, it may be considered that most of the EP objectives identified here are similar to those of developed countries. The objectives “improve security of energy supply” (Ec1), “improve system reliability” (Ec2), “increase economic development” (Ec3), “minimize environmental impacts and climate change impacts” (En1 and En2) are examples of objectives that are also common to EP activities in developed countries that fall into “three E” themes of energy security, economic revitalization, and environmental protection (Logan and James, 2009).

It is unclear, at this stage, whether the apparent convergence of objectives with the pattern of those from developed countries represents a fundamental nature, or whether it represents mostly borrowing from developed countries rather than going through a complete bottom-up process of identifying the fundamental objectives for each EP activity.

Regarding indicators and attributes, there were few similarities found between the indicators or attributes employed and the indicators previously proposed for use in local planning activities of developed countries. This may represent some specificity of these indicators to developed countries, but it also may represent a gap in the planning activities of the ECOWAS region. Attributes such as “new connections to the grid”, “trend in marginal costs of electricity” and “capacity to maintain and operate new technologies” can be pointed out as evidence that there is some specificity of attributes and indicators to regional objectives.

Implications:

- Identify whether additional objectives exist such as the local “implementability” or “maintainability” that may aid in ensuring that the plans resulting from EP activities are successfully implemented. This would be a potentially beneficial step to achieving the ambitious goals that have been set in the region for increased modern energy access, among others.

As a final remark, it should be noted that, despite the methodology adopted allowing for conclusions to only be drawn for ECOWAS member states, it is considered likely that the findings for the ECOWAS could be representative of other developing countries/regions as well, hypothetically with some adaptations.

Chapter 3

Development of a national energy planning methodology

3.1 Introduction

National EP is a complex activity requiring the evaluation of multiple segments of the energy supply and demand balance. The planning activity requires the involvement of multiple actors including stakeholders with diverse preferences, as well as the numerous DMs responsible for plan formulation and eventual implementation. Together, these actors must establish an energy strategy that seeks to fulfill multiple, often contradicting EP objectives.

A methodology to support this complex activity would be beneficial. This methodology would allow for the EP activity to be conducted in a strategic, systematic, and transparent manner supporting all the actors involved.

A review of EP activities within the ECOWAS found that not all member states are active in EP at the national, regional (multiple municipalities) and/or local energy level. In countries with EP activities, potential room for improvement was identified in terms of methodology robustness (evaluation of multiple alternatives and scenarios), their comprehensiveness (inclusion of multiple FE carriers and other concerns, e.g. DSM), as well as structure (identification of objectives, translation of these to quantifiable attributes, and inclusion of measurement and verification activities) (Lee and Leal, 2014).

Multi-criteria decision support based EP methodologies for specific contexts such as local municipality EP in developed countries and developing countries, as well as national EP for energy efficiency have been presented. Georgopoulou et al. (1997) developed a multi-criteria decision support approach for renewable local, island, EP. Georgopoulou et al. (2003) drew on multi-criteria decision approach research to structure a national action plan for energy sector GHG emissions mitigation. van Beeck (2003) created a decision support methodology for local EP in developing countries. Haydt (2012) addressed the issue of national energy efficiency plan development with a multi-objective decision support methodology. The works from

Catrinu (2006), Neves (2012) and Neves et al. (2015) presented multi-criteria decision support methodologies for EP at the local level.

The usefulness of MCDA in EP has been discussed in a number of works, and reviews of different applications have been presented (Diakoulaki et al., 2005; Løken, 2007b; Pohekar and Ramachandran, 2004; Wang et al., 2009). MCDA methodologies have been developed to aid energy planners in the evaluation of alternatives through more systematic approaches, allowing for multiple constructed policy alternatives to be evaluated and compared (Diakoulaki et al., 2005). The International Institute for Applied Systems Analysis (IIASA) Energy-Multi Criteria Analysis tool (ENE-MCA) from McCollum et al. (2012) was constructed to aid policy makers at the national level allowing for interactive assessment of options' performance on attributes measuring achievement in multiple objectives.

EP methodologies enabling actors to approach EP activities at the national level as a decision problem addressing multiple objectives that are specific to the contextual reality of developing countries have not been presented in previous works. In the absence of an applicable methodology for national energy systems master planning in developing countries a new methodology was required for the current work.

The following sections present the construction of a national EP methodology for use in supporting energy policy development in developing countries, specifically ECOWAS member states for the context of the current work.

The methodology consists of the three central activities of (1) Problem structuring, (2) Energy modeling and (3) Multi-criteria evaluation. These three activities are not performed strictly in a linear direction. The proposed activities in the methodology together with their connections are presented in Figure 3-1.

3.2 Problem structuring

The EP activity, like any complex problem, should be structured around a number of objectives that set the overarching purposes for which the activity is undertaken. This often includes several objectives that may be contradictory including economic, environmental, and reality (e.g. technology availability) aspects (Bouvy et al., 2010). Problem structuring is a procedure that aids in managing rather than reducing complex issues and is therefore helpful to DMs in reaching a comprehensive understanding of situations and reaching a common definition of the actual problem (Rosenhead, 2006; Ackermann, 2012).

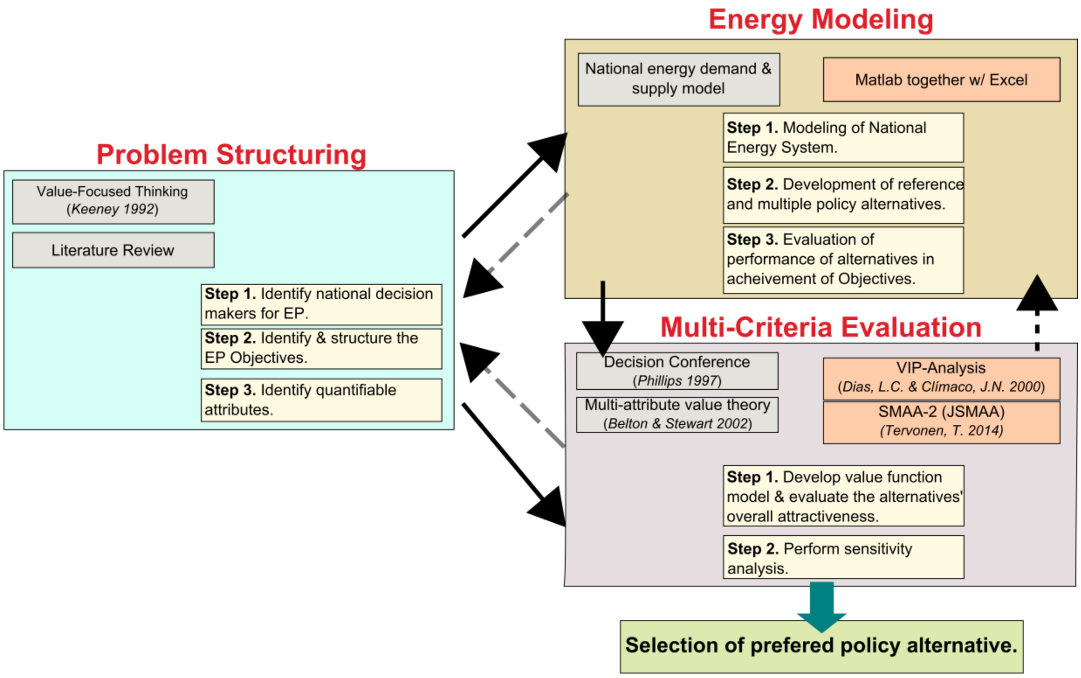

Figure 3-1 – Proposed energy planning methodology

Problem structuring methods (PSMs), also referred to as *soft* Operational Research (OR) methods arose from a need to account for the wider decision environment, which was often excluded from purely quantitative OR methods. PSMs were developed from efforts to ensure that a holistic approach was used to account for the widening boundaries of problems that included political, social and other drivers as well as the multiple actors involved in organizations making decisions. PSMs aid actors in developing an understanding of a system and learning how to make sustainable and systematic interventions in this system (Ackermann, 2012).

PSMs, according to Rosenhead and Mingers (2001), support actors in addressing “ill-structured situation problems”. PSMs aid in this movement from a poorly defined problem to a problem that can be formulated, modeled and quantitatively analyzed (von Winterfeldt and Fasolo, 2009). Decision making following Simon (1976) consists of the stages of (1) intelligence, (2) design, (3) evaluation and (4) implementation. Problem structuring is focused on these first two stages of understanding the problem and designing a structure to attend to it. This focus on the initial stages increases the chances of successful activities in the remaining 3rd and 4th stages (Ackermann, 2012).

According to Ackermann (2012) there are multiple benefits to the use of PSMs to support decision making. The first advantage is that it provides a method to manage complexity. The management of complexity aids in exploring multiple perspectives to the problem, widening the array of alternatives considered and enabling new alternatives to be identified. These allow for DMs to ensure that a more informed decision is reached. The second is the ability to attend to multiple perspectives in formulating the problem, and hence establishing a comprehensive view. In addition this supports ownership of, as well as commitment to an agreed solution. It also leads DMs to the understanding that multiple viewpoints exist, and that incorporating additional viewpoints supports the outcome of the work. The third benefit is the management of the process and content of a decision problem through the use of structured models. These models allow for the representation of divergent views in a structured format representing the larger picture of the problem. From this common representation of the problem, DMs can clearly understand the problem, avoid miscommunications regarding the components considered, and focus on solving the right problem.

3.2.1 Problem structuring methods

According to Winterfeldt and Fasolo (2009) there has been a growth in the past 40 years in the theory and practice in PSMs as well as in the number of methods available. In this regard they have become commonly accepted as an important branch in OR (Rosenhead and Mingers, 2001).

Decision analysis consists of a formal set of models and or tools with foundations in utility and probability theory that support decision making (Clemen, 1996). The *decision analysis structure* is a soft structure that is a formal representation of the decision problem that stops short of numerical modeling and analysis with which it is typically accompanied. At the core of this structure is the *decision frame*. This supportive *frame*work provides the scope of the problem to be addressed, the DMs and stakeholders together with their values, constructed alternatives evaluated for the range of concerns, and uncertainties. The structuring of decision problems for decision analysis is not limited to the framing step (1), but also the steps of (2) selecting appropriate structures, for a decision tree structure or a multiple objective structure, and (3) development of these structures in detail or refinement, (e.g. defining *fundamental* objectives and quantifiable attributes) (von Winterfeldt and Fasolo, 2009).

Rosenhead and Mingers (2001) make a distinction between (1) traditional methods and (2) alternative paradigm PSMs. The first, traditional methods, consist of methods that aim to quantify problems. They include approaches, which comprise single objective optimization, potentially require large amounts of data, and assume the perspective of a single decision maker treated as a passive object. The alternative paradigm of PSMs uses methods and models that seek alternative acceptable solutions, have a reduced data requirement, are transparent and aimed at clarifying the situation, including DMs as active subjects (Bell, 2012; Rosenhead and Mingers, 2001).

The practice of mixing PSM methods or multi-methodology use has become more common than it was in the early years of PSM. Multi-methodology use refers to both the utilization of multiple supporting PSMs as well as the combination of PSM with decision analysis (von Winterfeldt and Fasolo, 2009).

Rosenhead and Mingers (2001) and Ackermann (2012) reviewed the three commonly cited PSMs of Soft Systems Methodology (SSM), Strategic Options Development and Analysis (SODA) and Strategic Choice. The main theoretical premise behind these three methods is that a firm understanding of the overall situation and underlying system that links components or stakeholders contributes to the ability to addressing the situation and should be completed as a first step. The methods however differ in how this is completed and the steps that follow.

SSM, originally developed by Checkland (1981), begins with an analysis of the social, political, and cultural aspects underlying an organization and graphically represents this in a "rich picture." This picture aids in revealing the processes, structures, and relations in the organization and supports conversation and learning when used with the DM group. From this SSM moves to a focus on an idealized system to enable conceptualization of alternative systems and views that represent desired transformations. Comprehensive stakeholder involvement is of key concern in SSM, and alternative views are refined with the CATWOE mnemonic, or Customers, Actors, Transformation process, Weltanschauung, Owners, Environmental constraints (Ackermann, 2012).

SODA – Journey Making (Jointly Understanding Reflecting and NEgotiating strategy), which was initially developed for graphical representation of problems by groups, or individuals, has become commonly employed for developing organizational strategies (Eden and Ackermann, 1998; Rosenhead and Mingers, 2001). SODA relies on the development of cognitive and causal maps as graphical representations of the situation being addressed. Maps are developed by stakeholders involved either independently or in group. These maps detail the complex system underlying the situation and allow for a common understanding of convergent and divergent viewpoints among DMs (Ackermann, 2012).

Strategic Choice was developed in the framework of local and national planning activities which required the input of multiple stakeholders to aid participants to make strategic decisions. The method deals explicitly with uncertainties in the working environment, in the guiding values and objectives, and in choices in related activities (Rosenhead and Mingers, 2001). The method consists of the four stages of shaping, designing, comparing and finally choosing, which a group of DMs addresses together in a generally linear fashion. Shaping specifically applies to identifying relevant decision areas to address in the situation. Cycling through the stages has been recommended to ensure robustness of the outcomes.

A number of additional PSMs were also reviewed in Mirakyan and Guio (2014) for structuring an EP activity. The PSMs reviewed assist in identifying and making explicit relevant issues for planning activities. The methods of SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis, brainstorming, and the Delphi methods aid in identifying issues that are relevant to stakeholders and DMs. Additionally, the methods of value tree or objective hierarchy and means-ends objective network aid in providing a structure or framework of objectives to the issues identified. Brainstorming can also be used in later stages of identifying applicable alternatives.

The SWOT analysis is a widely recognized method that can support strategic planning activities. The SWOT allows for analysis of internal factors, referred to as strengths and weaknesses, and external factors, called opportunities and threats. These factors can be used to formulate a set of objectives (Jaber et al., 2015).

General brainstorming is a participatory activity that begins with eliciting ideas from participants in the identification of as many creative solutions as possible. Creativity is key in this activity and participants are expected not to criticize the inputs of other participants. It can be used in conjunction with additional methods such as value focused thinking (Keeney, 2012).

Another method applicable to identifying objectives is the SMART (Specific, Measurable, Achievable, Realistic and Timed) method. Specific here refers to the problem structuring phase of designing for a specific situation and corresponding needs.

The Delphi method consists of obtaining subjective expert judgments though a process of surveying and interviews. The method is used to identify and judge the value of objectives for a decision activity (Mirakyan and Guio, 2014).

The development of a Problem Tree allows for the disaggregation of a general problem into a detailed hierarchy of categories with their respective sub-problems. This is not a commonly cited approach, however it has been used in conjunction with other methods such as SWOT to identify objectives (Terrados et al., 2007).

Keeney (1992) presented the value-focused thinking method that allows DMs to start by identifying their values, which should be the *fundamental* driving force behind decisions, and establishing relevant alternatives that match these values. The value-focused thinking approach presents a systematic approach to identifying values, and can be used as a method in the establishment of objectives and attributes (Keeney, 1992). According to Keeney the first step is to set the *fundamental* objectives of the planning activity. *Fundamental* objectives are those that are both essential and controllable objectives, while means objectives are those that are important due to their implications for other higher level objectives. Identification of *fundamental* and means objectives lies in the answer to the question “Why is this objective important?” Keeney specified two possible answers, the first being that the objective describes a core reason for interest in the problem, meaning it is a potential *fundamental* objective. On the other hand, if the answer to the question brings an additional objective to light it is a means objective. This method allows for the development of a value tree or objective hierarchy. Here the *fundamental* objectives are linked global objectives. Similar to the value tree or objective hierarchy from value focused thinking, the means-ends or objective network aids in identifying *fundamental* objectives and linking them to means objectives through to quantifiable attributes allowing for their measurement.

Decision Conferencing as described by Phillips (2007) presents a structure for bringing together the key players who represent the main perspectives on an issue, as well as DMs within organizations or groups to facilitate the structuring of problems. Through a DC the objectives, attributes, and finally the results from the multicriteria methods can be verified and EP options can be chosen by DMs. The conference allows for participants to discuss important issues including the objectives of the activity, the building and immediate and continuous display and discussion of models, and interactive and iterative group activity of reviewing the results of the model. The DC brings together a facilitator as well as DMs in one space to structure and review the EP problem together.

3.2.2 Problem structuring and EP

The problem structuring activity is the investigation of issues that are considered critical to the problem together with stakeholder and DM involvement (Diakoulaki et al., 2005). Within EP and policy development, problem structuring methods aid in the identification of EP objectives and attributes as well as the evaluation and eventual selection of a preferred alternative. The objectives set for planning activities depend on the priorities of the DMs involved. The set of objectives that are considered most important differ between the DMs involved, as does the degree of importance of each objective in the planning problem being addressed.

In the planning stage DMs are required to choose between multiple alternatives and to make tradeoffs among objectives (Hobbs and Meier, 2003). During the planning stage DMs often start from the construction of alternatives thought to best fit the EP problem and then return to place objectives and arguments for choosing them (Keeney, 1992). This approach has been referred to as alternative-focused thinking and while it presents solutions to the decision problem it limits the planning process to pre-identified alternatives and does not help to design new alternatives.

There is a rapidly growing literature on the use of PSMs in EP related activities. The use in EP is often a multi-methodology approach for structuring in support of decision analysis activates. Neves et al. (2009) employed SSM for identifying the key issues, and objective hierarchy and means-ends network for structuring objectives and attributes in the development of a generic MCDA model for use in evaluation of EE initiatives. Haydt (2012) used the Delphi method to identify relevant EP objectives as well as value-focused thinking approaches to structure the objectives and quantifiable attributes. Neves et al. (2015) developed a cognitive and causal map in addition to an objectives hierarchy to support an evaluation of alternatives with a MCDA model at a DC event.

While the use in EP is growing, PSMs are not generally applied in practice. Mirakyan and Guio (2014) found that in most case studies the initial planning phase is not conducted by explicitly identifying objectives, formulating problems or developing a map or model of the situation. The planning and modeling are quantitatively conducted by an analyst or planner. Bagheri and Hjorth (2007) found that traditional modeling activities are ruled by a single entity that then explains results of modeling and planning to policy makers. This however does not support a learning activity, and in addition to analysts or modelers, DMs and stakeholders should be involved in a transparent process.

3.3 Application of problem structuring method

Problem structuring in the current work was done in support of a decision analysis problem and consisted of the three steps of (1) framing or identification, (2) development of a structure, and (3) refinement of this structure, as described in Section 3.2.1 (von Winterfeldt and Fasolo, 2009). MCDA is discussed in further detail in the following sections; however, it is discussed briefly here in relation to the problem structuring activity.

The research and case study were conducted for the national EP activity of Ghana[11], and hence were not conducted for a country relatively proximate to the location in which the research was undertaken. The case study country is a member of the ECOWAS in SSA and the current research was undertaken in Portugal. Due to travel constraints the researcher had limited contact with actors. Due to these limitations it was assumed that a PSM that allowed for limited contact between the actors involved was necessary.

For the framing stage of the PSM, in replace of a participatory method such as those described previously in Section 3.2.1, a detailed literature review was completed to identify potential implicit and explicit factors important for EP in the ECOWAS region. This literature review was complemented by the literature review of EP activities in the ECOWAS, Chapter 2, which identified common EP objectives.

Although a literature review was not ideal, it was decided that it would be applicable in the current case due to the limited interaction with actors. To compensate for this absence of participation and input from actors at the framing stage actors were invited to present feedback on the completed problem structure at a DC held as part of the case study (detailed in Section 6.3). In future EP activities, where access to actors is more readily available, the participatory PSMs of the new paradigm may be beneficial to the framing phase.

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[11] The country of Ghana, an ECOWAS member state, was chosen for the case study in the current work. The full justification for the choice of the case study country and a detailed description of it are presented in Chapter 5. However, it is important to specify the case study country here, due to considerations specific to the case study country discussed within the development of the national EP methodology.

In the second and third phases of structuring and refinement, the value focused thinking approach was beneficial in structuring the EP objectives into a hierarchy of *fundamental* objectives and a network of *means-ends* objectives. Here quantifiable attributes were identified which best represented the factors identified in the literature review. The refinement phase was also addressed in the DC and actors were invited to ask about and give feedback regarding the EP objectives. Also, time permitting, additional objectives or hierarchies could be structured and used for evaluation.

3.4 Framing the problem

The purpose of the current work was to evaluate how the use of additional context specific objectives may alter the results of an EP activity as compared to a generic set of objectives. Therefore, two sets of *fundamental* objectives were required. These consisted of the ECOWAS EP objectives as well as the context specific ECOWAS+ objectives. A third set was also evaluated for comparison purposes, which represented a set of objectives from a developed country, which could be generically adopted in EP activities. These three objective sets are defined later in Section 3.5.

The first set, or ECOWAS+ set of EP objectives consisted of the base set of ECOWAS EP objectives, but also included the additional implementation focused objectives. The methodology for structuring the problem that follows describes the process of identifying these additional implementation focused EP objectives.

The second set, or ECOWAS set, of EP objectives representative of the EP activities in the region was constructed based on the review of the state of the art of EP in the ECOWAS region (Detailed in Table 2-3 of Section 2.6.2). This work identified eight EP objectives that fell within the energy sector.

The third was the developed country set that consisted of EP objectives common to EP activities in developed countries. These EP objectives were identified after the ECOWAS and ECOWAS+ sets of objectives; recognizing that a set of the EP objectives, already identified, were generally applicable to activities in more developed countries.

To identify the ECOWAS+ objectives a literature review was completed to identify criteria that are influential in the implementation and sustainability of energy sector plans and projects. The literature reviewed consisted of 18 articles, 8 government, organization and company reports, and finally 5 news articles, presented in Appendix A.

The literature review resulted in identification of a preliminary set of 109 factors. An initial screening of factors was conducted to eliminate redundant or duplicate factors. The criteria obtained from the literature review were then evaluated in terms of their capacity to be developed into an objective rather than those characteristic of constraints. Constraint factors can be described as binary evaluation factors (e.g. availability of funds as opposed to minimizing costs). Next, factors that were not focused on technical measures but alternatively on promotional mechanisms were removed as this work concentrated on technical measures. It is acknowledged that promotional mechanisms are influential in the implementation of energy plans. Examples include financial incentives or information programs. There are many mechanisms, however, and these are often context specific and considered out of the scope of this work. Next, criteria considered fundamental were kept while removing circumstantial factors, such as government support for actions. A final list of 7 factors was established through this review. A flow-chart detailing the literature review process is shown in the Figure 3-2. The full set of factors and the filtering process is included in Appendix A. The final seven factors are presented in Table 3-1.

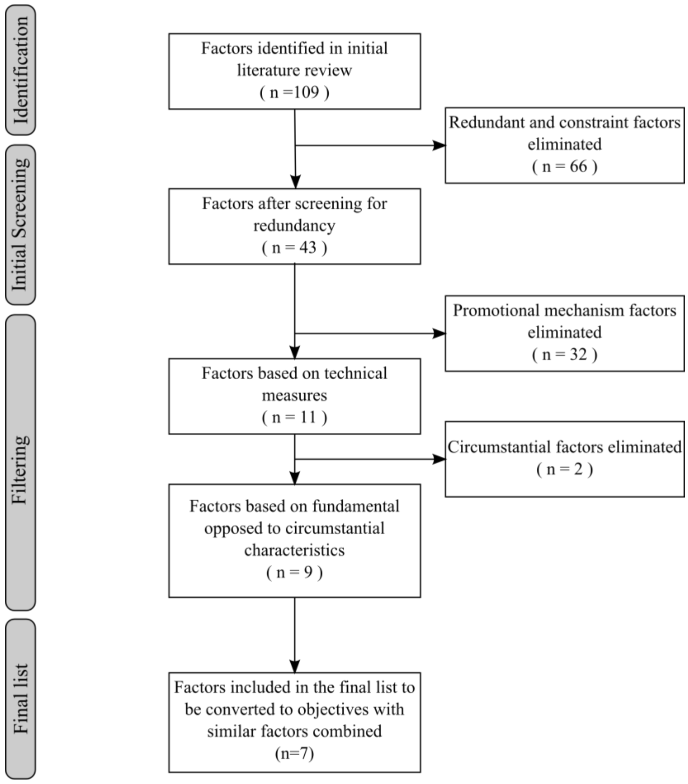

Figure 3-2 – Flowchart of literature review of implementation and sustainability factors

3.5 Structuring the problem

The seven factors, shown in Table 3-1, resulting from this literature review were not yet in a useful form, and they had to be translated into objectives. Using the value-focused thinking approach from Keeney (1992) the hierarchy of fundamental objectives and means-ends objectives network was established for each of the three EP objective sets. This was done through an analysis of the three sets of objectives, to identify the *fundamental* objectives and do identify objectives that were a means to an end.

Once a set of objectives was established, referred to as the ECOWAS+ set, it was compared with the set of generic ECOWAS objectives previously identified in the literature review of EP activities in the region, Chapter 2. These two sets of objectives are shown in Table 3-2.

Table 3-1 - List of factors for implementation and sustainability

Theme	Factor
Technology or system	Security of the PES Reliability of the FE supply Allows for productive uses of energy Maintainability of energy systems
Economic & Financial	Investment costs
Environmental	Contributions to climate change Impacts on local environment (including air pollution, water pollution and land degradation)

Table 3-2 - Comparison of ECOWAS and ECOWAS+ objective sets

ECOWAS objective set	ECOWAS**+** objective set
1. Maximize the security of the primary energy supply	1. Maximize the security of the primary energy supply
2. Maximize the reliability of final energy suply	2. Maximize the reliability of final energy suply
3. Maximize population with access to final energy	3. Maximize population with access to final energy
4. Minimize the influence of energy use on the global climate	4. Minimize the influence of energy use on the global climate
5. Minimize the impacts on the local environment (air, water, ground)	5. Minimize the impacts on the local environment (air, water, ground)
6. Minimize the costs (investment, operation & maintenance)	6. Minimize the costs (investment, operation & maintenance)
	7. Maximize the maintainability of the final energy system

The factor "*Allows for productive uses of energy*" was omitted as the corresponding objective reflects, in essence, the same concern as "*maximizing access to modern final energy supplies,*" identified in the original ECOWAS objective set. For this reason, it was not added as a separate fundamental objective. Here consideration of the productive uses was then considered in the quantifiable attribute used to measure the objective to *Maximize population with access to final energy* in the ECOWAS+ set of objectives.

The productive use of energy is inextricably linked to the provision of modern energy. The relation between productive uses of energy and economic development or poverty reduction is more readily seen in the standard definition of national energy productivity, or inverse of EI. Here the national energy productivity is equal to the ratio of national GDP to national energy consumption. Increased energy productivity results from either increased GDP or decreased energy consumption, which can result from increased energy efficiency or shifts in industry or other large energy demands. The direct uses of energy for productivity are then those that bring an increase in GDP as this can be directly related to income generation. Social and educational uses of energy, long considered unproductive uses, have been found to be indirectly linked to productivity. Recent work has also expressed a need to expand definitions of productive uses of energy to include social and educational uses together with direct income generating uses (Modi, 2001; White, 2002; Kamal, 2004; GNESD, 2007a; de Gouvello and Durix, 2008).

Therefore, the *productivity of energy use* factor was included in the provision of modern FE services EP objective. Modern energy carriers including electricity and LPG are more flexible than traditional fuels providing for a diverse set of FE services. Electricity even more so as no other FE carrier can equal the instant and effortless access to FE services that electricity can offer to users. Electricity provides an unparalleled flexibility being convertible to light, heat, mechanical energy, and chemical potential (Smil, 2005). Electricity can be used silently as well as cleanly, at the point of use, and with minor adjustments it can be precisely adjusted to provide for desirable speeds and accurate control of particular processes (Schurr, 1984). Flexibility is also related to the adaptability of systems to meet current and future needs, or evolutionary capacity (Wicklein, 1998).

The maintainability of energy systems factor is seen to have influenced the only unique objective added to the ECOWAS+ objective in objective 7, to *maximize the maintainability of the FE system*.

Objective 6 to M*inimize the cost (investment, maintenance and operation)* while not being identified in the original ECOWAS set was added as it was assumed that this was a common EP objective in developing and developed countries whether it as explicit or not. This objective replaced the original objective from the ECOWAS to *improve the ability to provide affordable energy*. Energy access is also influenced by the affordability of energy to populations, and considerations of affordability are often discussed together with energy access (Banerjee et al., 2008; Winkler et al., 2011). For this work the affordability of the energy supply is considered to be influenced through the objective of minimizing costs in addition to government influences including subsidies. The dimension of subsidies is considered circumstantial and outside of the scope of the current work.

The focus of the current work is on the ECOWAS+ objective set, however the fundamental objective hierarchies for the three respective objectives sets are shown in Figure 3-3 to 3-5.

The shaded boxes represent the level where attributes are defined. Applicable quantifiable attributes were identified for each of the EP objectives. These are detailed together with methods for their measurement in the sections that follow.

The objectives that were identified from the ECOWAS and ECOWAS+ objective sets to be applicable to a generic EP activity in developed countries were also extracted to construct a respective representative Developed Country EP objective set (Figure 3-5).

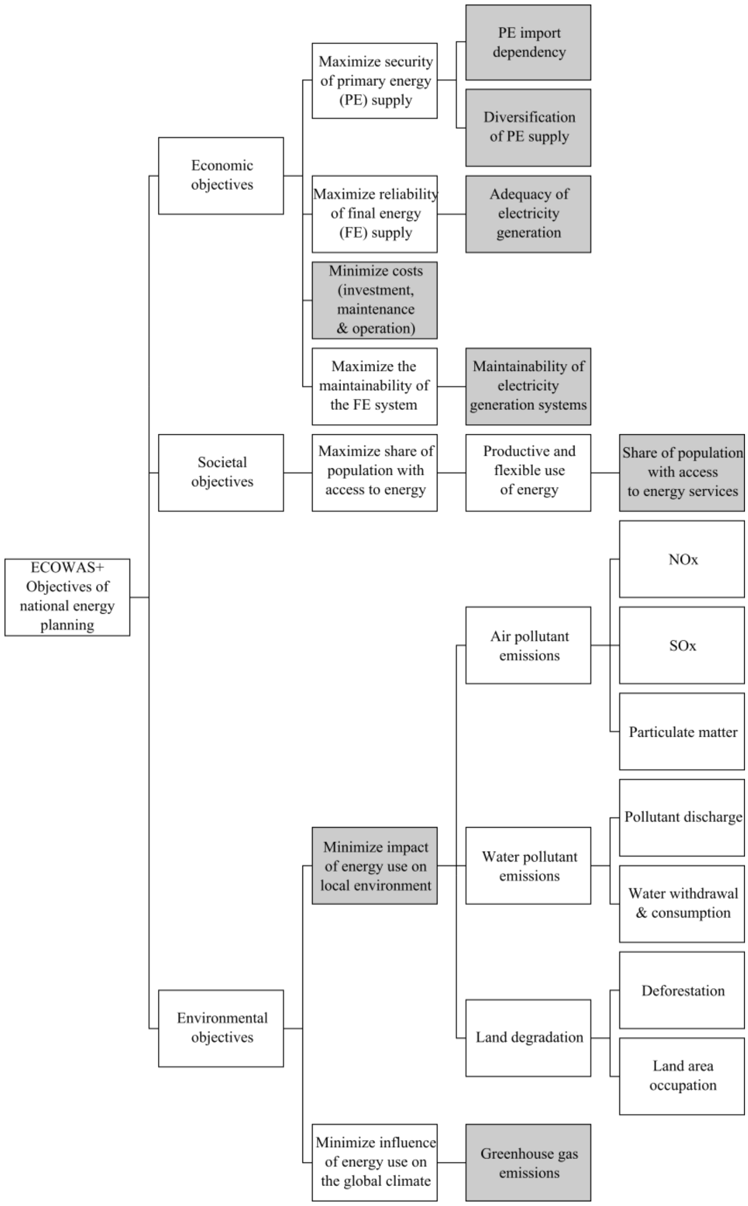

Figure 3-3 - Fundamental objectives hierarchy: ECOWAS+ objective set - ***The shaded boxes represent the level where attributes are defined.***

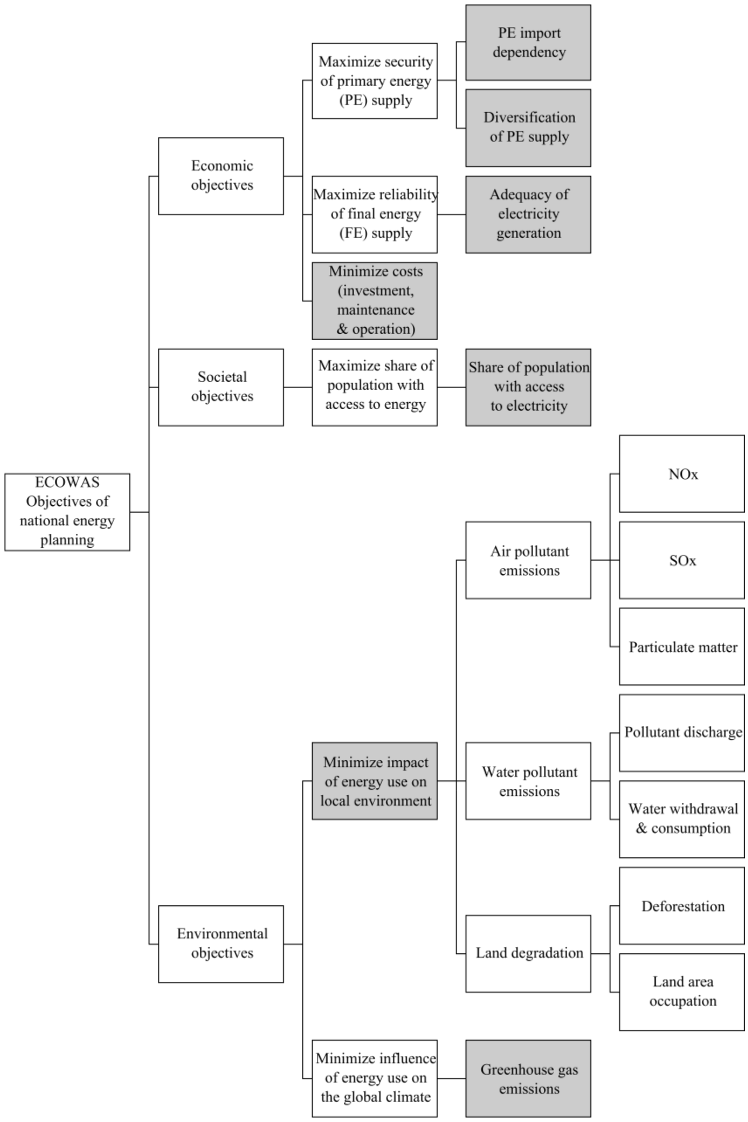

Figure 3-4 - Fundamental objectives hierarchy: ECOWAS objective set - *The shaded boxes represent the level where attributes are defined*.

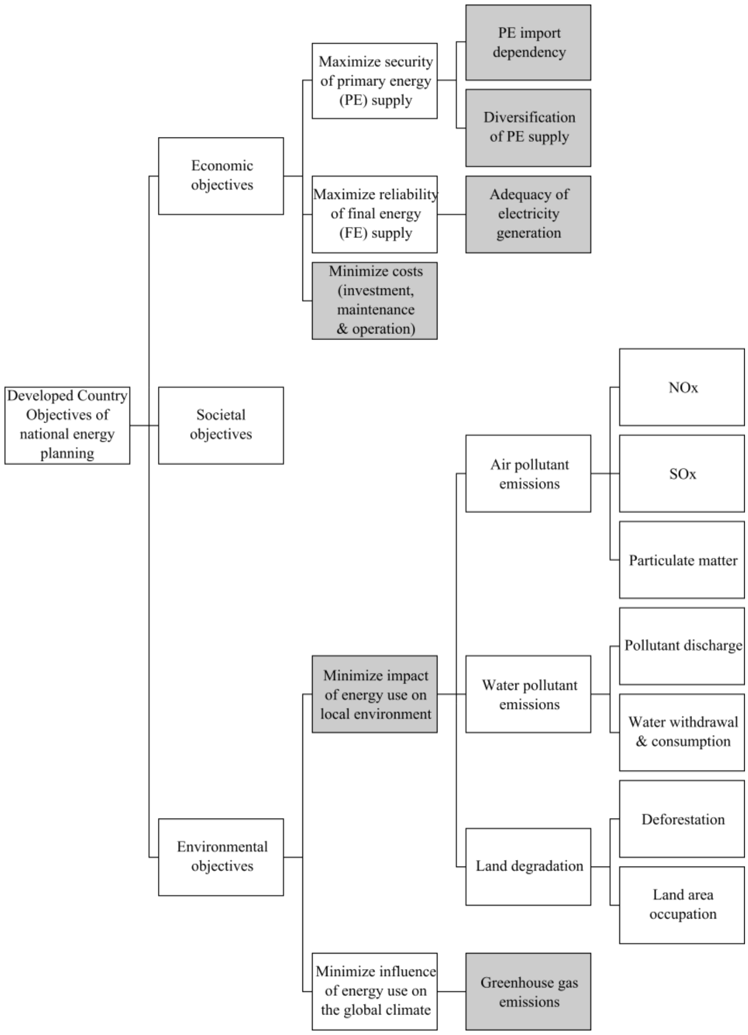

Figure 3-5 - Fundamental objectives hierarchy: Developed Country objective set - ***The shaded boxes represent the level where attributes are defined.***

3.6 Refining the problem

After identifying and structuring the EP objectives, the next stage in structuring the problem was refinement. This includes detailing the scope of the individual EP objectives and establishing the quantifiable attributes and the methods in which they would be measured.

The ECOWAS+, ECOWAS, and Developed Country objective sets are summarized in Table 3-3 to allow for comparison of the objectives and attributes between the different sets.

In the selection of attributes Keeney and Gregory (2004) suggested that priority should be given to natural attributes, where these are not available a constructed attribute is designed, and if this is not possible or does not provide a valuable result a proxy attribute can be used. However, some well-established proxy and constructed attributes are widely accepted and often used in the place of natural attributes. Examples of these include, use of the proxy attribute of CO_{2eq} emissions for the objective to minimize global environmental impact, or the constructed attribute of the Human Development Index (HDI) to measure the level of development.

For this work priority was given to natural attributes, identified by literature review, which clearly measure what was defined by the objective. In the case that an adequate constructed attribute could not be designed an alternative proxy attribute was identified. The objectives and attributes selected were discussed and verified with DMs as part of the case study.

Table 3-3 - Energy planning objective sets and corresponding attributes

Objectives	**Attributes** ECOWAS+	ECOWAS	Developed Countries
1. Maximize the security of the primary energy (PE) supply.	Constructed attribute of Import Dependency & Diversification of PE supply.		
2. Maximize the reliability of final energy (FE) supply.	Constructed attribute of Electricity generation system adequacy.		
3. Maximize the maintainability of the FE system.	Constructed scale of maintainability.		
4. Maximize access to FE supply.	Constructed attribute of share of population w/ access to energy services.	Constructed attribute of share of population with access to modern energy carriers.	
5. Minimize costs (investment, maintenance & operation).	Total costs of energy infrastructure (invest., maint., & oper.)		
6. Minimize influence of energy use on global climate.	CO_{2eq} emissions from the energy system.		
7. Minimize impact of energy use on local environment.	Constructed scale of energy system impact on air, water, & land.		

3.6.1 Maximize the security of the PES

Concerns for energy security are at their root based on the understanding that the continued functioning of an economy and society requires uninterrupted flows of energy (Kruyt et al., 2009). It is important to delineate the terms of energy security and security of supply, which are often used interchangeably (Kruyt et al., 2009; Löschel et al., 2010). Despite the importance of energy security concerns, a consensus has not been reached for a concise established definition for the term (Brennan, 2007). This can be seen in the many definitions put forth, as well as the variety of metrics employed to measure energy security (Chester, 2010).

The IEA (2007) described energy *in-security* as resulting from "from the welfare impact of either the physical unavailability of energy, or prices that are not competitive or overly volatile.'' Bohi, Toman et al. (1996) argued that security "refers to the loss of economic welfare that may occur as a result of a change in the price or availability of energy." Winzer (2012) presented a collection of recent security of supply definitions and described energy security as dealing with sources of risk that may have a variety of impacts on continuity of energy supply, continuity of energy services, continuity of the economy and impacts on environment and society. Lacking a clear definition it has become an "umbrella" term for numerous policy objectives (Winzer, 2012). This is due to the evolving nature of energy security, which has broadened in recent times from a previous focus on the availability of key fossil fuels to include multiple contributing dimensions (Yergin, 2006).

Sets of dimensions, which contribute to the overall energy security, have been proposed by multiple authors of which availability of energy resources is a common dimension (Löschel et al., 2010). Work from CIEP (2004) discussed the five dimensions of availability, accessibility import dependency, energy demand, political relations, and environmental concerns in a review of European security of energy supply. The IEA (2007) presented three dimensions consisting of adequacy, affordability and reliability of supply. The work from APERC (2007) based energy security indicators on four dimensions of availability, accessibility, acceptability, and affordability of fuels. Sovacool and Mukherjee (2011) presented five dimensions of availability, affordability, technology development and efficiency, environmental and social sustainability, and regulation and governance. Kruyt et al. (2009) identified an emerging shift in the dimensions presented in previous work towards the four dimensions of availability, accessibility, affordability, and acceptability.

For this work energy security is considered the overarching structure, within which security of (PE) supply is considered to be a dimension. The dimensions of affordability, acceptability, and environmental and social sustainability are considered circumstantial and also outside the scope of this work as they can be influenced by government. The structure of energy security also includes dimensions of continuity of the FE supply as well international politically motivated concerns considered out of the scope of this work. Security of supply can be considered as consisting of long, medium, and short-term considerations. Medium and short-term security can be described to fall into activities related to the reliability of the FE system. Short-term concerns here are related to system operational security, and medium-term has to do with system generation or capacity adequacy to meet FE demand, all of which is outside the scope of the PES. These medium-term concerns will be addressed in the objective that follows dealing with reliability of the FE system (REKK, 2009).

This work focused on the long-term availability of the PES and efforts to hedge against future, possibly unforeseeable interruptions. These considerations are on imported crude oil and petroleum products as well as indigenous resources. Stirling (1999) argued that the most comprehensive strategy to deal with the complete ignorance of future long-term developments is to design for diversity of supply including considerations of variety, balance and disparity. The current work will concentrate on the first two of these considerations that are linked to diversity and import dependency. The third consideration, disparity, or the nature and degree to which each supply differs from another according to Stirling (1999) is a complicated property to quantify,

3.6.1.1 Attribute - Maximize the security of the PES

The plentitude of attributes employed as metrics for energy security can be broadly separated into two categories (1) aggregated metrics and (2) simple metrics of global PES, national PES, FE supply and other economic, political and environmental measures.

The simple metrics typically consist of measurements of a single concern. Global PES simple metrics deal with global PE resources and consumption (Turton and Barreto, 2006). FE supply concerns evaluate the PES requirements for the FE transformation system, FE system key indicators including plant ages, locations, and FE demand among others (IAEA, 2005; Markandya et al., 2005; Bazilian et al., 2006; Kruyt et al., 2009; Bhattacharyya, 2011). Other measures include prices, price stability, value of annual imports, economic indicators, political stability or risk, and energy subsidies (Bazilian et al., 2006; Kruyt et al., 2009). These simple indicators, while presenting clear information on specific concerns in energy security, do not individually present a comprehensive evaluation, and a mix or dashboard of indicators is often required (Sovacool et al., 2011).

Composite indicators, while obscuring some information may offer a comprehensive evaluation. These indicators are typically measures of diversity or market shares adopted from other fields (Sovacool et al., 2011).

The Shannon diversity index (also referred to as the Shannon-Weiner or the Shannon-Weaver diversity index) was originally developed to measure what is referred to as entropy within the field of information theory by Shannon and Weaver (1948). It has since been adopted as a measure of diversity and balance in other fields including energy systems analysis and specifically in energy security analysis. Jansen (2004) employed the Shannon index in the development of four attributes of PES, which build upon a measure of diversity to include additional dimensions. These consisted of diversity, diversity with import dependency, diversity and import dependency with socio-political stability, and finally diversity, import dependency, socio political stability and resource depletion. APERC (2007) presented a similar set of five PES indicators for diversity, diversity and import dependency, net carbon intensity of the PES, net oil import dependency, and Middle East oil import dependency. Löschel et al. (2010) adapted the Shannon index to include indigenous renewable supply considerations in addition to imported PE supplies.

An additional index of diversity, the Herfindahl-Herschmann index, originally developed to measure diversity in biology by Simpson (1949) was employed to measure the market concentration of PE suppliers, countries, at the global level. This was then adapted to include political stability concerns of suppliers. The combination of this measure and considerations of the PES shares of individual countries was used to develop a PE security index (Blyth and Lefevre, 2004; IEA, 2007).

Blyth and Lefevre and the IEA (2004; 2007) argued that additional measures are applicable to energy supplies with restrictions that do not allow them to follow market fundamentals such as long-term import contracts on piped natural gas. While the case study country, Ghana, to be presented, is served by a natural gas pipeline, it was considered at this stage that the use of natural gas and its import will be considered within the measure of diversity and import dependency.

For the current work two attributes, (diversity and diversity with import dependency) presented by Jansen (2004) and APERC (2007) employing the Shannon index allow for measurement of availability measuring variety and balance in the PES fulfill the requirements for a measure of PE security. These concerns are applicable to the concerns of diversity and import dependency in the current work. These attributes have been previously employed in the context of West Africa (Adenikinju, 2008).

The first energy security attribute (ESA_1) provides a measure of diversity of the PES as shown in Eq. 3-1. The second attribute, ESA_2, permits an adjustment of the first attribute for a measure of diversity with a consideration of import dependency. The second attribute, shown in Eq. 3-2, will be used for evaluation of PES security in the current work.

$$ESA_1 = \frac{D_1}{D_{max}} = \frac{D_1}{\ln U} \quad [-] \qquad \textbf{Eq. 3-1}$$

$$D_1 = -\sum_{r=1}^{U} p_r \ln(p_r) \quad [-]$$

Where:

ESA_1*:* The first attribute measuring diversity of PES [-]

D_1: Shannon-Weiner diversity index[12] [-]

D_{max}: Maximum possible value of the Shannon-Weiner diversity index [-]

U: Number (count) of PE resources used. [-]

p_r: Share that PE resource *r* in total primary energy supply (PES), for all resources in *p=1…U*: (U PE resources used) [%]

[12] In the calculation of the Shannon-Weiner diversity index where p_r, the value of the share of PE resource *r* in total PE supply, approaches zero an “intermediate form” is reached in D_1 . L’Hopital’s rule is used in this case to evaluate the limit to obtain the final value which in this case is $\lim_{x \to 0} x \ln(x)$=0 (Wolfram Alpha LLC, 2015).

ESA_2 incorporates ESA_1, but extends the measurement to also consider the dependency on PE supply imports.

$$ESA_2 = 1 - \frac{ESA_{import}}{ESA_1} \quad [-] \qquad \textbf{Eq. 3-2}$$

$$ESA_{import} = \frac{D_2}{D_{max}} = \frac{D_2}{\ln U} \quad [-]$$

$$D_2 = \sum_{r=1}^{U} c_r p_r \ln(p_r) \quad \text{Where: } \mathrm{c}_r = 1 - \mathrm{m}_r \quad [-]$$

Where:

ESA_2: Measure of PE diversity and import dependency [-]

ESA_{import}: import reflective measure of PE diversity [-]

D_2: Shannon-Weiner diversity index, import reflective. [-]

D_{max}: Maximum possible value of the Shannon-Weiner diversity index [-]

U: Number (count) of primary energy resources used. [-]

c_r: Correction factor for PE resource *r*, calculated as the share of PE resource *r* provided by indigenous sources. An increased indigenous PE supply of resource *r* results in an increased value for D_2. [-]

p_r: Share of primary energy resource *r* in total PES, for all resources in r=1…U: (U primary energy resources used) [%]

m_r: Share of net import in PE supply of resource *r* [%]

3.6.2 Maximize the reliability of FE supply

The IEA (2007) refers to upstream and downstream energy security. The first term refers to PE supplies and secondary energy fuels, which are inputs to the energy systems (e.g. electricity supply system or other), or as Winzer (2012) described, those having to do with the continuity of the commodity supplies. The latter, downstream, is concerned with the interruptions in FE carriers (e.g. electricity). In the present work the latter, downstream, considerations will be considered within the objective of maximizing reliability of the energy system, while upstream energy security concerns are considered in PE security.

Reliability of the energy system therefore will refer to the downstream continuity of services, supplies, or the energy system's ability to meet customer demand with a consistent and dependable supply of quality energy.[13]

Physical connection or proximity to FE supplies does not ensure that end-users have access to a reliable supply of FE. Therefore, the reliability of energy supplies is also of concern. Reliability refers to confidence in the system's ability to provide energy for the energy services that are demanded by the end-users. Interruptions in the delivery of FE make for an unreliable energy system.

3.6.2.1 Attribute - Maximize the reliability of FE supply

The reliability of the FE system can be described in short and long(*er*)-term. The short term is characterized by operational security or quality of the energy supply on the scale of minutes, hours or days, and considerations are typically ex-post indicators measured from results rather than projections. They include measurements of unforeseen disturbances on the order of minutes to hours. Examples of indicators of short-term reliability include the distribution service quality indicators of System Average Interruption Index (SAIDI), which is measured as the minutes per customer per year of interruptions, and Energy not supplied (ENS) measured in GWh (REKK, 2009). Evaluation of the reliability of the system at this level requires complex models of the energy systems allowing for analysis of short-term reliability, on the order of seconds, minutes, and hours that was out of the scope of the current work.

A long(*er*)-term consideration of reliability was made here of the adequacy of the energy systems. These include electricity generation (possibly transmission) adequacy measures comparing generation capacity and demand (or transmission capacities for natural gas for example or possibly provision capacities for fuel wood as well) (NERC, 2010).

While the adequacy of generation does not provide for forecasts of the short-term indicators of reliability indicators of SAIDI or ENS, it does however evaluate the ability to meet final demand, and as such has ramifications for the short-term reliability.

The evaluation of generation adequacy from UCTE (2008) fulfilled the requirements of reliability for the current work, which was a long term measure of reliability, Eq. 3-3.

[13] Technically, system reliability, different from quality, is the consistent and dependable supply of an energy carrier to the user, while quality for electricity systems this term refers to a variety of electromagnetic phenomena that characterize the voltage and current at a given time and location and normative descriptions which set acceptable boundaries for these phenomenon (REKK, 2009). Quality considerations could also be made in respect to other carriers, based on criteria specific to those carriers.

$$Adequacy_y = 100 \times \frac{RMGC_y}{NGC_y} \quad [-] \qquad \textbf{Eq. 3-3}$$

$$RMGC_y = RAC_y + Import\ capacity - peak\ load\ demand_y \quad [MW]$$

$$RAC_y = NGC_y - unavailable\ capacity_y \quad [MW]$$

Where:

$Adequacy_y$: Adequacy of electricity generation in year *y* [-]

$RMGC_y$: Remaining margin of electricity generation capacity in year *y* [MW]

RAC_y: The remaining generation capacity that results from the difference of the NGC and the unavailable capacity in year *y* [MW]

NGC_y: The net installed generation capacity in the given year [MW]

$unavailable\ capacity_y$: Generation capacity that is unavailable in year *y* calculated with the availability factor of each generation capacity technology type [MW]

3.6.3 Maximize the maintainability of the FE system

The maintainability of the FE system refers to the ability of the system to function with minimal difficulties for normal maintenance and unscheduled repairs. According to Smith (2001) the time that any technology or system is properly functioning and available for use is dictated by both the reliability and the maintainability of that technology or system. However, Smith (2001) goes on to state that the maintainability of a system is seldom a single measure of a system, but based on separate metrics. Opare and Park (2011) defined maintainability as a measure of the time required for skilled personnel to restore a system or failed service to a properly functioning state adhering to established standards and procedures.

Within maintainability three main categories of analysis can be identified, specifically the proveness of technologies, (2) ease of maintenance, and (3) existence of local capacity.

Within the first category, proveness of technologies, Lai et al. (2011) evaluated the viability for implementation of carbon capture and storage technologies in Malaysia based on the criteria of the Technology Readiness Level (TRL), potential speed of deployment, current and future costs, and potential scale of abatement. The TRL originally developed by National Aeronautics and Space Administration (NASA) to evaluate technology maturity based on 7 defined levels of readiness for deployment was adopted by the US Department of Energy for use in research projects (Mankins, 1995, 2009). The TRL evaluates proveness or novelness of emerging technologies for initial deployment, however the current work concentrates on the applicability of existing technologies to a specific geographic region. Technology maturity is also described within technology life-cycle S-curves that detail the introduction, maturity and saturation of technologies. This life-cycle analysis credited to Little (1981) describes these four stages of the S-curve being linked to two criteria, the economic competitiveness of technologies and the implementation into products and processes. At the saturation stage a technology becomes a base technology of use in society. Gao et al. (2013) evaluated the technology life-cycle based on an analysis of the patents existing for specific technologies.

The second category in maintainability is the ease of maintenance and is related to the short-term measures of reliability. The maintainability at this level is related to the availability of spare parts and facilities for maintenance and unscheduled repairs. Smith (2001) described common measures dealing with the (1) mean time to failure as well as (2) mean time between failures, which can be evaluated for specific technology types. The mean down-time measures the overall time that a technology is not usable. The mean time to repair is similar, however it is measured as the time from which it has been realized that a failure has occurred until the time that the technology is again usable, overlapping with down-time (Smith, 2001).

The third category is the availability of local capacity to install, maintain, operate and repair technologies. Archibugi et al. (2009) reviewed a number of metrics for the evaluation of the technological capacities of nations. The majority of the metrics focus on innovation and not only capacities for specific technologies. The *Summary Innovation Index* (SII) evaluates a nation's innovation potential through a structure of 25 indicators within the categories of innovation inputs and innovation outputs (European Commission, 2015a). The *Global Summary Innovation Index* (GSII) a composite indicator evaluates the national innovation performances compared to international competitors (European Commission, 2015b). The *Technology Index* within the overarching *Growth and Competitiveness Index* from the World Economic Forum evaluates innovative capability, technology transfer, diffusion of new information and communications technologies (WEF, 2015a). Also from the World Economic Forum is the *Technological Readiness Index,* within the *Global Competitive Index,* which measures firms' capacities to adopt new technologies and specific requirements that support this adoption. It also evaluates research and development investments, and human capital (WEF, 2015b). The *Knowledge Index* (KI) from the World Bank evaluates four main categories, specifically accountability of the economic and institutional system, education level of the population, innovation capability of the nation, and the diffusion of information and communication technology (World Bank, 2012). The te*chnology Advance Indicator* from the United Nations Industrial Development Organization (UNIDO) assesses the concentration of the productive sector of a country in the technology industries and ability to compete on the international level in advanced sectors (UNIDO, 2005). Finally is the *Technology Activity Index* from the United Nations Conference on Trade and Development (UNCTAD) that appraises technological activity through an evaluation of labor force involved in research and development activities and the number of patents and scientific publications (UNCTAD, 2005) These evaluation techniques are concentrated on innovation potential and the research and development potential of nations. The current work is focused on the aspect of maintaining technologies in the energy sector.

The scope of this objective is currently limited to the electricity generation system. The maintainability of the energy system within this work consists of three components, namely the (1) proveness of the technology in the West African and African context, (2) availability of Parts and Maintenance, and (3) local capacity for installation operation and maintenance.

3.6.3.1 Attribute - Maximize the maintainability of the FE system

In the absence of a comprehensive natural or proxy attribute for the maintainability of the FE system, a constructed scale attribute with defined levels is employed. The attribute evaluates the maintainability of the electricity generation system as a proxy of the FE system as providing electricity access is an important concern in developing countries.

A defined levels constructed scale consisting of four distinct levels was established for the current work. Each level is defined by an appropriate description of maintainability. The maintainability is defined by three criteria in each level; proveness of the technology in the West African and African context, availability of parts and maintenance, and local capacity for installation operation and maintenance. The defined levels are presented in Table 3-4, and it is seen that lower values on the scale are more desirable than higher ones.

For the case study, generic electricity generation plants are considered, and each generation technology type is assigned a maintainability level, based on information available on the generation type and expert evaluation. In future cases in which specific generation technologies are to be considered within a planning activity, each individual generation plant can be evaluated separately for maintainability by the analysts and DMs involved. It is acknowledged that assigning defined levels to the technologies may be highly subjective to the DM and their expertise; however, this could be done within a conference environment allowing for discussion and compromise. A sensitivity analysis conducted in the current work will also evaluate alternative evaluations. The maintainability levels for the specific case of Ghana, the case study country, are presented in Table 3-5.

A weighted sum method is used where the maintainability is equal to the product of the weights of each technology in the electricity generation scheme, w, and their evaluated level of maintainability, *L*.

There are limitations to the approach used here. The constructed scale of maintainability is a qualitative scale in which the numbers 0, 1, 2, and 3 were assigned arbitrarily. Also within the weighted sum method the difference from 0 to 1 is assumed to be equal to the difference from 1 to 2 and etc., which may not be consistent with actual differences. Granted that these limitations exist, there was a need for a simple synthetic indicator for the current work. Additionally, care was taken to explicitly define each level 0, 1, 2 and 3 ensuring that each would represent similar value differences. The defined levels and the approach should of course be discussed with DMs in further applications to ensure their applicability.

$$Maintainability_y = \sum_{u=1}^{Y} w_{u,y} \times L_u^M \quad [-] \qquad \textbf{Eq. 3-4}$$

$$\sum_u w_u = 1 \; and \; 0 \leq \; w_u \; \leq 1 \; for \; all \; u = 1 \ldots Y$$

Where:

$w_{u,y}$: Share that the technology represented in the total installed capacity of electricity generation technologies in year *y* for all installed capacity generation technologies *u=1…Y* [%]

L_u^M: Evaluated level of maintainability (*M*) of the installed generation technology type *u* [-]

3.6.4 Maximize access to the FE supply

Access to energy is of course available to almost all of the world's inhabitants in various forms from solar energy, biomass, and others. The use of these PE resources however can, at times, be burdensome, dangerous, unhealthy, unsustainable, or unproductive as discussed in the introductory Chapter 1. An example is the use of wood fuel for daily cooking needs, which may require long hours of resource collection, often by women and children, in areas possibly distant from the home. It also requires constant care of the fire, implying the inhalation of fumes by those present. In addition, cooking with biomass is typically done with the standard three-stone arrangement, resulting in an inefficient transfer of heat.

Energy access, in the context of the current work, refers to access to modern energy carriers such as electricity and gas and the modern energy services that they enable (e.g. gas cooking, electric lighting, and etc.). This is opposed to traditional energy carriers such as biomass. The definition in this work entails energy at the household level.

It is acknowledged that these considerations hold true for the productive and transport sectors, however access in these sectors is not considered in this work. It is assumed that with access at the household level "cottage industries", which entail productive work, often informal sector work, at the household level, here accounted for in Service sector. The access in the remaining sectors (e.g. Industry and Service), is assumed to be available with the connection of urban and rural areas to electricity or other FE carriers.

There is no consensus on one way in which to define and measure FE access. Multiple definitions exist and are established according to the purpose of the measurement or the data available (IEA, 2006a; Brew-Hammond, 2010; Sokona et al., 2012).

Table 3-4 - Defined levels of constructed scale of maintainability

Attribute level	Representative Maintainability
0	**Highly Maintainable:** **Proveness**: Technologies are proven in area of application with multiple case studies and current use in energy systems.
	Parts and maintenance: All or the majority of general and/or crucial parts are locally available & or produced, and local maintenance facilities exist, and other parts are easily encountered abroad.
	Local capacity: Existence of local technical capacity for installation, maintenance and use as well as local educational and research facilities familiar with technologies.
1	**Reasonably Maintainable:** **Proveness**: Technologies are proven in geographical area of application with multiple case studies completed.
	Parts and maintenance: A number of general and/or crucial parts and maintenance facilities are locally available, while the other parts can be found abroad.
	Local capacity: Some existence of local technical capacity for installation, maintenance and use, while technical capacity can be easily found abroad.
2	**Marginally Maintainable:** **Proveness**: Technologies are proven in geographical area of application with at least one case study of application completed.
	Parts and maintenance: Some parts and maintenance facilities are available in geographical area of application, while majority of parts and facilities for maintenance are still found abroad.
	Local capacity: Some existence of local technical capacity for installation, maintenance and use, while majority of technical capacity is found abroad.
3	**Not Maintainable:** **Proveness**: Technologies are not proven in geographical area of application.
	Parts and maintenance: Parts and maintenance facilities are not available in geographical area of application. All parts and facilities for maintenance are found abroad.
	Local capacity: No local technical capacity for installation, maintenance and or use. All of technical capacity is found abroad.

Table 3-5 - Technology maintainability levels - Ghana

Conversion technology	Maintainability level [Table 3-4]	Description	Reference
Oil	0	Decommissioned prior to plan implementation.	(EC, 2006b)
Coal	1	No examples in West Africa but common in South Africa.	(Anku, 2012)
Gas Turbines	1	Several countries of the ECOWAS currently have gas turbines (GT) and combined cycles (CC) running either on natural gas or on liquid fuel. The majority of these GT and CC are dual fuel allowing burning either gas or liquid fuels. Various manufacturers are represented on the continent. In the base year there was limited installed capacity in Ghana.	(ECOWAS, 2011)
Combined Cycle Gas Turbines (CCGT)	1	See gas turbines.	
Large hydro	0	Large Hydro - highly maintainable as large hydro dams were constructed in 1965 in Ghana, and are therefore well established.	(EC, 2006b)
Small hydro	1	Here small hydro considered to be less maintainable than large hydro. Nigeria has installed capacity.	(Ohunakin et al., 2011)
Large Wind-onshore	2	Wind installed capacity in Africa is small – both in measured by installed capacity, and by its contribution to the energy mix. 96% of 1,000MW of installed capacity located in North African Countries.	(Mukasa et al., 2013; GWEC, 2014)
Large Wind-offshore	3	No known Installations in Africa.	
Small wind	2	Assumed to have the same maintainability level as Large wind farms.	
Solar PV Plant	2	Small solar PV plant was installed in Cape Verde in 2010, by a European company. No known small plants in other ECOWAS countries.	(ECREEE, 2013b)
Concentrated Solar Plant	3	No installations on the African continent. Projects are planned in Algeria, Morocco, Egypt and South Africa. In 2009 the IEA estimated a maximum installed capacity <600MW, where parabolic trough and central tower receiver are the most common. Linear and parabolic dish types have few commercial examples.	(Greenpeace et al., 2009; IEA, 2010b)
Stand-alone Solar (building)	3	Considered same as small Solar PV plant as there is some installed capacity.	(EC, 2006b)
Landfill Biogas	3	The vast majority of waste disposal sites in Africa are open dumps. Landfill siting is usually decided based upon factors like access to collection vehicles rather than electricity generation. Sites lack minimum design and personnel requirements for biogas use. Some countries have made improvements to landfill practices in northern Africa and South Africa.	(IEA, 2009; Botes, 2012)
Municipal solid wastes	3	No known implemented technologies in ECOWAS or West Africa. Exploratory papers and pilot studies are still underway.	(Fobil et al., 2005; Amoo and Fagbenle, 2013; Ofori-Boateng et al., 2013; Scarlat et al., 2015)

Biomass and wood wastes	2	Some installed capacity in forestry and industry sector SNEP.	(EC, 2006b)
Nuclear	3	South Africa has only installed capacity of 1,900MW. Ghana has small (30kW) research reactor.	(Nyarko, 2007; US EIA, 2015b)
Large Solar PV Plant	3	No known capacity in ECOWAS. First large installation has been discussed in Ghana with foreign installer.	(Ayre, 2014)
Wave Power	3	Negligible installed capacity worldwide. No installed capacity in Africa.	(IEA-ETSAP, 2010)
Tidal-range Barrage Power	3	0.5GW installed capacity worldwide. No installed capacity in Africa.	See above
Tidal Stream Power	3	Negligible installed capacity worldwide. No installed capacity in Africa.	See above
Hybrid Diesel & Solar Minigrid	2	Negligible installed capacity in Ghana, or working examples in ECOWAS. Diesel generators are common, however hybrid solar is negligible.	(EC, 2006b)

Definitions include physical connections to energies (in the case of electricity), ability to connect or use FE carriers, or physical proximity or the offer of access, as well as energy poverty considerations, which have multiple definitions (Pachauri and Spreng, 2011; Sokona et al., 2012).

A definition of physical connections, to the electricity grid for example, is supply side oriented in that it provides a count of how many end-users are connected to the grid. It does not consider the demand of energy users for cooking, lighting, or other (Bazilian et al., 2010). Also, it does not account for their capability to use the energy that is available as electrical end-use devices must be purchased to harness the energy implying affordability concerns in addition to those of connection and energy-use costs. Considering the ability (physical proximity or offering) to connect or use a FE carrier is also a supply side oriented measure, as it assumes that the user does not make decisions on infrastructure investment or development of energy systems (Winkler et al., 2011). It also assumes that once energy is supplied to a location, the population of that location then has the ability to connect, where as with the physical connection definition above this may not always be true.

Despite having access to energy, the affordability of energy is a limiting factor often discussed together with energy access (Winkler et al., 2011). For this work the affordability of the energy supply is considered to be influenced through the objective of minimizing costs, as the costs of the energy infrastructure and supply system affect the end-use energy prices, which is further discussed in Section 3.6.5, with the attribute of costs.

An alternative to the measure of access to energy, a supply side perspective, is the measure of lack of energy services, a perspective more in line with a demand side approach. Measuring the deprivation of energy services allows for quantification of demand for energy services and permits the demand to be met by energy carriers that are the most suited for the specific context. The measure of access to a particular fuel (e.g. electricity) is biased to one carrier and leaves little room for choice by the end-user, whose energy demand may vary due to many different issues. This approach however requires the identification of novel indicators and or attributes (Bazilian et al., 2010). Additionally, this approach can be expressed from an inverted definition as the provision of FE services.

3.6.4.1 Attribute - Maximize access to the FE supply

The current work approaches energy access within two different EP structures, namely the (1) ECOWAS+ objective set and (2) ECOWAS objective set, which were detailed in the fundamental objective hierarchies, Figure 3-3 to 3-4.

Within the ECOWAS objective set, energy access follows the traditional supply side measure of access to electricity of the population. Here the population is approximated by the number of households with access however the population can be estimated with the assumptions on household sizes [population/household]. Considerations for the ECOWAS objective set approach are presented in Table 5-4 with the Case Study in Chapter 5.

The evaluation methodology for the ECOWAS objective set is completed following Eq. 3-5.

$$Access_{1,y} = \frac{\sum_{p=1}^{3} Share_{1,p,y} \times HHS_{p,y}}{\sum_{p=1}^{3} HHS_{p,y}} \quad [\%] \qquad \textbf{Eq. 3-5}$$

Where:

$Access_{1,y}$: Share of households with access to electricity in year *y* following the traditional method for evaluation (*1*) [%]

$Share_{1,p,y}$: Percentage of households of population type *p* in year *y* that are assumed to have access, following evaluation method (*1*) [%]

$HHS_{p,y}$: Households of population type *p* in year *y* [households]

Within the ECOWAS+ objective set the approach is from the provision of modern FE services to the population. A constructed attribute was developed to measure access which populations with specific energy carrier portfolios have to energy services. Ten representative household energy carrier portfolios were identified. These were combinations of energy carriers that households may have access to in a given year. Each portfolio was evaluated in respect to the number of FE services that could be provided with each portfolio. Considerations for the ECOWAS+ objective set approach are presented in Table 3-6. The energy carrier portfolio access rate assumptions for the reference projection are presented in Table 5-6 with considerations of the case study.

The evaluation methodology for the ECOWAS+ objective set is completed following Eq. 3-6. It is acknowledged that this approach assumes that all the FE services considered are of equal importance, which may not be the case. This assumption should of course be discussed with DMs in further applications to ensure that the approach is relevant.

$$Access_{2,y} = \frac{\sum_{p=1}^{3}\sum_{m=1}^{S} Share_{2,p,m,y} \times HHS_{p,y} \times Services_{m}}{\sum_{p=1}^{3} HHS_{p,y}} \quad [-] \qquad \textbf{Eq. 3-6}$$

Where:

$Access_{2,y}$: Constructed value evaluating access in year *y*, with the FE service method for evaluation (*2*), to FE services that lies on the range of 0 to 12 as 12 energy services are assumed [%]

$Share_{2,p,m,y}$: Percentage of households in population type *p* with access to portfolio *m* in year *y*, following evaluation method (*2*) [%]

$Services_{m}$: FE services assumed available to households with access to portfolio *m* [count of FE services]

As 100% of the population is assumed to have access to fuelwood, all FE carrier portfolios whether stated or not have access to fuelwood. The assumptions regarding energy access are presented in detail in Section 5.5 which presents the case study.

Table 3-6 - Energy carrier portfolios and respective FE services provided in current work

		Energy Services											
Energy carrier Portfolios	Energy Services Provided [count]	Cooking	Water heating (domestic)	Lighting	Water pumping - mechanical power	Refrigeration	Freezing	Clothes washing - mechanical	Computer & IT	Clothes drying- mechanical	Dishwashing mechanical	AC - mechanical	Entertainment - devices - electronics
Fuelwood (FW)	2	●	●										
FW + Kerosene	3	●	●	●									
FW + LPG	2	●	●										
FW + Ker + LPG	3	●	●	●									
Electricity- Grid (Elec-G)	12	●	●	●	●	●	●	●	●	●	●	●	●
Elec-G + LPG	12	●	●	●	●	●	●	●	●	●	●	●	●
Electricity- MiniGrid (Elec-MG)	12	●	●	●	●	●	●	●	●	●	●	●	●
Elec-MG + LPG	12	●	●	●	●	●	●	●	●	●	●	●	●
Electricity- Standalone (Elec-SA)	12	●	●	●	●	●	●	●	●	●	●	●	●
Elec-SA+ LPG	12	●	●	●	●	●	●	●	●	●	●	●	●

3.6.5 Minimize costs of the energy system

The energy costs, which consumers pay, are directly influenced by the costs incurred by utilities in providing energy. The costs for energy use can be divided into the actual costs for generation and delivery of energy carriers and the margin above these costs that provide profits to utilities and governments.

As the profit margin is dependent on government and utility policies or subsidy programs this remained outside of the technical focus of the current work. Costs are also influenced by the margin of profit that utilities or governments set above the costs necessary for provision of energy, as well as subsidies or possible incentives from these actors. The scope of this work did not include government or energy utility set profit margins or subsidy programs, as these are promotional mechanisms set by policy makers & context specific. This work concentrated on technical measures. These were specifically the investment, operation, and maintenance of energy systems in the implementation of the energy plan.

Costs here were considered as those that are incurred by the government and or utilities in the investment, operation, and maintenance of energy systems, namely transformation technologies, transmission and distribution, and petroleum refining.

Investment costs included the purchase, delivery and installation costs of technologies. Operation and maintenance costs include fixed and variable costs. The fixed costs consisted of the labor expenses, including overheads for operation and maintenance of a system or plant and the operation and maintenance materials, excluding fuels. Fixed costs are typically modeled as a fixed component of currency per year, or for power systems as currency per unit power per year (Sheblé, 2006). In addition to fixed costs are variable costs that include fuel costs. Variable costs can be measured in terms of output, as cost per unit of electricity generated, or alternatively as a fixed operation and maintenance cost per year per unit of capacity (IEA, 2010c).

3.6.5.1 Attribute - Minimize costs of the energy system

A natural attribute of costs was chosen and is divided into the Investment costs and Operation and Maintenance costs.

Evaluation of costs is limited to those that will be incurred due to new investments laid out in the EP activity alternatives, both investment and operation and maintenance. The costs incurred for already existing equipment that continues to be used or is retired during the EP activity will not be considered as it is assumed that these “background” costs will be identical for all alternatives.

Cost will be evaluated as the total of all applicable costs from electricity generation capacity for grid, minigrid and standalone systems. When it is applicable, additional petroleum refinery capacity costs will be considered. Eq. 3-7 was used for total costs of implementation in year y.

The costs for transmission and distribution line extensions were included. Calculation of costs for transmission and distribution line investments followed the work by Rosnes and Vennemo (2009) for SSA that based growth of stock on energy demand. It was assumed that the installed stock will grow at half the rate of electrical energy demand. Investment costs for transmission and distribution are then calculated based on newly installed lines.

$$Total\ Cost_y = \sum_{h=1}^{Q} Cost_{h,y} \quad [Monetary\ Units] \qquad \textbf{Eq. 3-7}$$

Where:

$Total\ Cost_y$: Total costs from all cost sectors considered, h=1 – electricity generation capacity, h=2 – transmission and distribution system, & h=3 – New connections (access) & h=4 - petroleum refineries in year *y* [Monetary units (US dollars)]

$Cost_{h,y}$: Total annual cost from sectors considered for h=1 - electricity generation capacity, h=2 – transmission and distribution system, h=3 – New connections (access) and h=4 – petroleum refineries, in year *y* [Monetary units (US dollars)]

The costs for electricity generation are shown in Eq. 3-8 to Eq. 3-10. The corresponding costs assumed for the specific case of Ghana, are shown in Table 3-7, Table 3-8, and Table 3-9.

$$Cost_{h=1,y} = \sum_{g=1}^{W} Inv_{g,y} + \sum_{g=1}^{W} O\&M_{g,y} \quad [Monetary\ Units] \qquad \textbf{Eq. 3-8}$$

$$Inv_{g,y} = \left(\mathrm{Cap}_{g,y} - \mathrm{Cap}_{\ g,y-1}\right) \times \mathrm{inv.cost}_g \times 1{,}000 \quad [Monetary\ Units] \qquad \textbf{Eq. 3-9}$$

$$O\&M_{g,y} = \left[\mathrm{Cap}_{g,y}^{elec\ gen} \times Oper.\&\ Maint.cost_g \times 1{,}000\right] + \left[\frac{Q_{i=5,y}^{Total\ TDL} \times share_{g,y} \times Availability_g^{elec\ gen}}{\eta_g} \times Fuel\ cost_g\right] \quad [Monetary\ Units] \qquad \textbf{Eq. 3-10}$$

Where:

$Inv_{g,y}$: Investment cost of newly installed capacity of technology type g in year *y* [Monetary units (US dollars)]

$O\&M_{g,y}$: Operation and maintenance cost of technology type g in year *y* [Monetary units (US dollars)] g=1…W: all newly installed electricity capacity

$\mathrm{Cap}_{g,y}^{elec\ gen}$: Total installed capacity of technology type g in year y [MW]

$\mathrm{inv.cost}_g$: Unit investment cost for technology type g [Monetary units (US dollars) /kW]

$Oper.\&\,Maint.cost_g$: Annual unit operation and maintenance costs for installed capacity [Monetary units (US dollars) /kW]

$Q_{i,y}^{Total\ TDL}$: The total FE carrier i, considering losses (TDL) for year y [MWh]

$share_{g,y}$: Share that technology g represents in generation mix [%]

η_g: Efficiency of electricity generation technology g [%]

$Availability_g^{elec\ gen}$: The availability factor for electricity generation technology g [%]

$Fuel\ cost_g$: Cost of fuel that corresponds to technology g [Monetary units (US dollars)/ktoe]

Table 3-7 - Investment costs: Ghana electricity generation technologies

	Ghana	African continent – sensitivity analysis		
Technology	Investment cost [US $/kW]	Minimum [US $/kW]	Maximum [US $/kW]	Lifetime [years]
CCGT	1,200	538	1,678	30
Gas Turbines	400	350	520	30
Coal- Subcritical	1,400	600	2,100	40
Nuclear (various technologies)	3,600	1,556	5,863	60
Large Hydro- dam, pump, run of river	4,833	757	19,330	80
Small Hydro	3,130	1,970	11,598	25
Large wind Onshore	1,500	1,223	3,716	25
Large wind Offshore	2,680	2,530	6,083	25
Small wind	1,500	-	-	25
Solar PV Plant	3,700	2,590	7,381	25
Concentrated Solar Power (CSP)	10,140	4,990	10,140	25
Small Solar PV (Buildings)	3,910	3,180	7,310	25
Biogas from landfills for electricity	2,340	2,170	9,925	30
Biomass & Waste - Municipal waste	5,020	3,240	20,502	30
Biomass CHP	3,715	2,800	5,420	30
Wave Power	7,900	6,800	9,000	25
Tidal-range Barrage Power	5,250	5,000	5,500	80
Tidal-Stream Power	6,900	6,000	7,800	25

References: (EC, 2002; Rosnes and Vennemo, 2009; IEA, 2010c, 2011a; Anku, 2012; IRENA, 2013a)

Table 3-8 – Operation and maintenance costs: Ghana electricity generation technologies

Technology	Ghana O&M cost [US $/kW]	African continent – sensitivity analysis Minimum [US $/kW]	 Maximum [US $/kW]
CCGT	25	12	69
Gas Turbines	20	18	47
Coal- Subcritical	44	21	53
Nuclear (various technologies)	120	62	261
Large Hydro- dam, pump, run of river	58	33	523
Small Hydro	63	12	316
Large wind Onshore	22	22	321
Large wind Offshore	80	76	474
Small wind	22	-	-
Solar PV Plant	48	39	709
Concentrated Solar Power (CSP)	201	200	321
Small Solar PV (Buildings)	59	48	535
Biogas from landfills for electricity	89	82	1,465
Biomass & Waste - Municipal waste	283	248	432
Biomass CHP	141	106	206
Wave Power	200	-	-
Tidal-range Barrage Power	115	-	-
Tidal-Stream Power	150	-	-

References: (EC, 2002; Rosnes and Vennemo, 2009; IEA, 2010c, 2011a; Anku, 2012; IRENA, 2013a)

Table 3-9 – PE supply costs for electricity generation - Ghana

PE Supply	Fuel cost [US $/ktoe]
Crude oil - Import	497,350
Natural gas – Import	219,765
Coal - Import	154,162
Diesel – Import and Domestic	671,423

References: (EC, 2006c; Anku, 2012; IRENA, 2012)

The calculation of transmission and distribution costs is completed following the procedure shown in Eq. 3-15 to 3-13. The corresponding costs assumed for the specific case of Ghana, the case study country, are shown in Table 3-10 and Table 3-11.

$$Cost_{h=2,y} = \sum_{b=1}^{Z} Investment_b + \sum_{b=1}^{Z} Operation\ \&\ Maintenance_b$$

Eq. 3-11

$$[Monetary\ Units]$$

$$Investment_{b,y} = \frac{Q_{i=5,y}^{Total\ TDL} - Q_{i=5,y-1}^{Total\ TDL}}{Q_{i=5,y-1}^{Total\ TDL}} \times Growth_{\ b} \times Stock_{b,y-1} \times inv.cost_b$$

Eq. 3-12

$$[Monetary\ Units]$$

$$Operation\,\&\,Maintenance_{b,y} = value\ of\ stock\ \times Oper.\&\,Maint.cost_{b} \quad [Monetary\ Units] \qquad \textbf{Eq. 3-13}$$

Where:

$Q_{i,y}^{Total\,TDL}$: The total FE carrier *I*, considering transmission and distribution losses (TDL) for year *y* [ktoe]

$Growth_{b}$: Growth rate of line type *b* where b=1 is transmission and b= 2 is distribution [%]

$Stock_{b,y-1}$: Total stock in distance of line type b in year y [km]

$inv.cost_{b}$: The unit investment cost of line type b [Monetary units (US dollars) /km]

$value\ of\ stock$: Total value of existing stock, compounded from base year, [Monetary units (US dollars)]

$Oper.\&\,Maint.cost_{b}$: The operation and maintenance cost as a share of the total value of existing stock [%]

Table 3-10 - Transmission and Distribution Investment costs - Ghana

Line type	Voltage level [kV]	Unit cost [US $/km]	Lifetime [years]
Transmission	161	108,450	30
Sub-transmission	69	108,450	30
Distribution_33kV	33	25,000	30
Distribution_11kV	11	25,000	30
Distribution_0.4kV	0.4	14,500	20

References: (Africon, 2008; Rosnes and Vennemo, 2009; Kemausuor et al., 2014) & calculations

Table 3-11 – Transmission and Distribution Growth rates and Operation and Maintenance costs - Ghana

Line type	Growth rate [Share of change in electrical energy demand %]	O&M costs [Share of installed stock value %]
Transmission	0.5	0.6
Distribution	0.5	0.6

References: (Rosnes and Vennemo, 2009)

The costs for new connections or energy access costs were based on the population type and the connection type (e.g. urban grid, rural grid, minigrid, and standalone systems). The costs for each new connection type are shown in Table 3-12 for the specific case of Ghana, the case study country.

$$Cost_{h=4,y} = \sum_{p=1}^{3}\sum_{c=1}^{4} Connections_{p,y} \times Share_c \times Connect\ Cost_c\ [Monetary\ Units] \quad \textbf{Eq. 3-14}$$

Where:

$Connections_{p,c}$: Number of households newly connected in year *y* [households]

$Share_c$: Share of new connections met by connection type *c* [%]

$Connect\ Cost_c$: Cost per new connection of type *c* [Monetary units (US dollars) / household]

Table 3-12 - Electricity connection costs (Access) - Ghana

Connection type	Connection cost [US $/household]
Urban Grid extension	500
Rural Grid extension	1,550
Minigrid	1,325
Stand-alone installation	800

References: (Rosnes and Vennemo, 2009)

The cost considered for petroleum refineries was that of investment costs, operation and maintenance. These were assumed to be heavily influenced by the sale of petroleum products. The oil refinery costs when applicable are based on specific costs for installed capacity in the case study country. The costs for specific interventions are presented in Table 3-13 for the specific case of Ghana, the case study country.

$$Cost_{h,,y} = Investment_{intervention}\ [Monetary\ Units] \quad \textbf{Eq. 3-15}$$

Where:

$Cost_{h,,y}$: Costs for specific interventions in the oil refinery TOR [Monetary units (US dollars)]

$Investment_{intervention}$: Cost for installed capacity for each specific *intervention* considered [Monetary units (US dollars)]

Table 3-13 – Petroleum refinery intervention costs - Ghana

Petroleum refinery intervention	Additional capacity [bbl/day]	Total investment cost [US $]
1	30,000	7.50E+07
2	15,000	3.75E+07
3	25,000	6.25E+07

References: (EC, 2006c)

Energy system projects are capital intensive, requiring large investment costs. These are typically financed in the form of a loan, where an initial down payment is required at the time of purchase and the remaining cost is spread over a certain number of years N, in addition to annual interest, calculated at a rate i. The operation and maintenance costs will be considered to be paid in full annually. Then annual investment costs for a project required to accumulate to a given present investment with given interest rates and number of years can be calculated by the familiar uniform capital recovery formula as follows for project j in year y (Bhattacharyya, 2011). The investment costs for all new electricity generation as well as petroleum refinery capacity is then calculated with Eq. 3-16.

$$Investment_{y=1,tech} = Down\ payment \quad [Monetary\ Units] \qquad \textbf{Eq. 3-16}$$

$$Investment_{y>1,tech} = c = \frac{int \times P_{loan}(1+int)^N}{(1+int)^N - 1} = \frac{int \times P_{loan}}{1-(1+int)^{-N}} \quad [Monetary\ Units]$$

Where:

int : The fixed annual interest rate [%]

N : The loan's term in number of years (or number of yearly payments) [years]

P_{loan} : The loan amount or the loan's principal. This is calculated by the difference of the total investment cost and the initial down payment. [Monetary units (US dollars)]

The fixed annual interest rate *i*, and the loan's term, *N*, will depend both on the total costs of projects and their expected lifetime. Operation and maintenance costs will be paid annually for all years from year *t* when installation is made until the operational lifetime of technology (*tech*).

3.6.6 Minimize impact of the energy system on the global climate

GHG emissions have been identified as a driver of global climate. Human activities have resulted in increased emissions of GHGs (e.g. CO_2, CH_4, N_2O, and halocarbons). Of these GHG emissions CO_2 has been identified as the most influential driver of global climate.

The GHG emissions from fossil fuel combustion have been identified as the largest share of anthropogenic contribution to global GHG emissions. The reliance on fossil fuels as primary energy supplies for energy systems has resulted in increased GHG emissions globally. The energy sector is typically responsible for over 90% of CO_2 and 70% of all GHG emissions in developed countries (IPCC, 2006a).

GHG emissions from the energy sector are attributed to combustion of fossil fuels and fugitive emissions from four main activities. These activities comprise the exploration and exploitation of PE resources, conversion of PE resources into FE carriers within both refineries and electricity generation plants, transmission and distribution of FE carriers and use of FE carriers in stationary and mobile applications (IPCC, 2006a). The combustion of fuels here refers to those that are intentionally combusted within applications to produce mechanical work or heat for a process and not the use of hydrocarbons in industrial processes (e.g. heat released from chemical reactions).

Of the main energy sector activities, on the national level, the stationary combustion of fuels and mobile combustion activities are responsible for 70% and 25% of GHG emissions respectively. Fugitive emissions from the energy sector arising from the extraction, transformation and transportation of energy amount to a small share of total emissions (IPCC, 2006a).

The current work will evaluate energy sector GHG emissions arising from the three main emission sources at the national level, namely stationary combustion for production of electricity, mobile combustion for transportation, and refinement of crude oil.

3.6.6.1 Attribute - Minimize impact of the energy system on the global climate

The attribute of CO_2 equivalent emissions (CO_{2eq}) is a commonly used proxy of the energy system's influence on global climate, and it was used as a quantifiable attribute in this work (Haydt, 2012). The guidelines for national inventories of GHG emissions from the Intergovernmental Panel on Climate Change (IPCC) provide a standardized procedure for calculation of energy sector emissions (IPCC, 2006a). The IPCC guidelines meet the United Nations Framework Convention on Climate Change (UNFCCC) requirements for national accounting, of which the ECOWAS members are members (IPCC, 2006a; UNDP, 2015b).

Considerations are to include the transformation of primary to FE as well as energy use in the Transport sector. The IPCC guidelines offer three separate tiers for accounting. Each tier represents a progressively more detailed approach based on default emissions factors, national or regional factors, and activity or technology specific data for tier 1, tier 2 and tier 3 respectively.

The current work will account for emission from mobile and stationary sources consisting of:

- Electricity generations (PE to FE transformation).
- Transportation: Road, Rail, Water & Aviation.
- Petroleum refining.

Country specific data was not available for all the sources considered, and it was assumed that of the current work tier 1 default emission factors would be sufficient for the analysis. Future work could substitute the emissions factors for country specific values as well as tier 2 or tier 3 calculation methodologies.

The annual GHG emissions are calculated as the total of emissions from the separate sources considered following Eq. 3-17. The default emissions factors used for this work are presented in Table 3-14 and 3-15 for the specific case of Ghana, the case study country.

$$GHG_{f,y} = \sum_{d=1}^{R} GHG_{f,d,y} \, [kton/year] \qquad \textbf{Eq. 3-17}$$

Where:

$GHG_{f,d,y}$: Total emissions of GHG f=1…N from emission source sector, d=1 – electricity generation (stationary), d=2 petroleum refining (stationary) and d=3 transportation [kton/year]

For stationary combustion in the generation of electricity and petroleum refining the procedure follows Eq. 3-18.

$$GHG_{f,d,y} = \sum_{r=1}^{U} PES_{r,d,y} \times emission\ factor_{f,r} \times unit\ conversion_{r} \, [kton/year] \qquad \textbf{Eq. 3-18}$$

Where:

$GHG_{f,d,y}$: Total emissions of GHG f=1…N from emission source sector, d=1 – electricity generation (stationary), d=2 petroleum refining (stationary) and d=3 transportation [kton/year]

$PES_{r,d,y}$: PES combusted for electricity generation (d=1) or petroleum refining (d=2) of fuel type *r* in year *y* [ktoe]

$emission\ factor_{f,r}$: Default emission factor of GHG *f* for fuel type *r* [kg/TJ]

$unit\ conversion_{r}$: Factors to convert units for result [kg/kton & ktoe/TJ]

The evaluation of emissions from mobile sources for tier 1 is similar to that of the stationary sources, however each separate subsector and transport type is considered. At more detailed tiers of analysis, emissions can be related to distances traveled etc., however for this work emissions are based on the fuel combusted as in Eq. 3-19.

$$GHG_{f,d,y} = \sum_{k=1}^{O} \sum_{s=1}^{P} \sum_{i=1}^{M} Q_{k,s,i,y} \times emission\ factor_{f,r} \times unit\ conversion_{r} \, [kton/year] \qquad \textbf{Eq. 3-19}$$

Where:

$GHG_{f,d,y}$: Total emissions of GHG f=1…N from emission source sector, d=1 – electricity generation (stationary), d=2 petroleum refining (stationary) and d=3 transportation [kton/year]

$Q_{k,s,i,y}$: FE demand for FE carrier *i* for transport type *s* in transport subsector *k* in year *y* [ktoe]

$emission\ factor_{f,r}$: Default emission factor for fuel type *r* [kg/TJ]

$unit\ conversion_r$: Factors to convert units for result [kg/kton & ktoe/TJ]

Table 3-14 – Default GHG emissions factors- Stationary combustion - Ghana

Stationary combustion	Default emission factor		
Fuel	CO_2 [kg of GHG/TJ]	CH_4 [kg of GHG/TJ]	N_2O [kg of GHG/TJ]
Electricity generation			
Natural gas	56,100	1	0
Landfill Gas	54,600	1	0
Municipal Wastes[1]	95,850	30	4
Wood/wood waste	112,000	30	4
Diesel	74,100	3	1
Coal	94,600	1	2
Petroleum refineries			
Residual fuel oil	77,400	3	0.6
Ethane	61,600	1	0.1

1. Assumed 50% non-biomass fraction and 50% biomass fraction

Reference: (IPCC, 2006b)

Table 3-15 - Default GHG emissions factors- Mobile combustion - Ghana

Mobile combustion	Default emission factor		
Fuel	CO_2 [kg of GHG/TJ]	CH_4 [kg of GHG/TJ]	N_2O [kg of GHG/TJ]
Road			
Gas/Diesel Oil	74,100	4	4
Motor Gasoline	69,300	33	3
LPG	63,100	62	0.2
Aviation			
Kerosene-aviation	71,500	0.5	2
Water			
Gas/Diesel Oil	74,100	7	2
Motor Gasoline[1]	69,300	7	2
Rail			
Gas/Diesel Oil	74,000	4.15	28.6

1. Assumed same values for motor gasoline and pre-mix gasoline.
Reference: (IPCC, 2006c)

The GHG equivalent is then calculated by the multiplication of the GHG emissions by the associated global warming potential for the specified time range. The sum of these equivalent GHG emissions is then calculated for the mix of GHG emissions considered to find the total CO_{2eq}, here referred to as total GHG, as shown in Eq. 3-20. The current work follows the IPCC (2006c) in using 100 year GWPs. The GWPs for the GHG considered in the current work are shown in Table 3-16.

$$Total\ GHG_y = \sum_{f=1}^{N} GHG_{f,y} \times GWP_f\ [kton] \quad \textbf{Eq. 3-20}$$

Where:

$Total\ GHG_y$: The total CO_{2eq} in year y [kton]

$GHG_{f,y}$: The total emissions of GHG f, for GHG f=1…N, in year y [kton]

GWP_f: Global Warming Potential of of GHG f [-]

Table 3-16 - Global Warming Potentials of GHGs - Ghana

Global Warming Potential – 100 year time horizon		
CO_2	CH_4	N_2O
1	21	310

Reference: (Hartmann, D.L et al., 2013)

3.6.7 Minimize impact of the energy system on the local environment

The potential impacts that the national energy system may have on the environment are numerous, as are the metrics that are used to measure them. These impacts result from the exploration, generation, delivery, and utilization of energy in its many forms (i.e. PE resources and FE carriers). One way to categorize these impacts is in the form of global impacts and local impacts. Impacts on the global scale are those that have global affects despite the location in which each respective activity is conducted, for example the previously discussed GHG emissions impact on global climate. On the local scale energy systems may impact the quality of air, water and land as well as other dimensions.

The local environmental impacts are the result of air, water and solid waste pollutants. These pollutants can impact the quality of the local environment in multiple ways. For example, pollutants released into the air can impact air, water and land quality. However, typically specific pollutants are used as proxy measures for impacts on specific dimensions of the local environment due to the predominant impact that they have.

The local environmental impacts are often evaluated in the dimension of land, air and water quality. Torchio et al. (2009) discusses local environmental impacts from district energy systems in regards to human health effects and concentrated on air pollutants. Mancarella and Chicco (2009) also concentrated on air pollutant emissions within local environmental impact of cogeneration facilities. Feeley Iii et al.(2008) discussed the effects on water resources caused by electricity generation, namely water withdrawal and water consumption, due to needs for cooling in thermal generation and as a driver of turbines in hydro-electric generation. Jay (2010) evaluated local impacts from energy systems in the dimension of land use, landscape, soil, biodiversity, and noise. The measurements for land use and protection of green areas were used for evaluation of land use and landscape. Rovere et al.(2010) assessed the local environmental impact of energy system expansions within the dimensions of water, land and air quality with the metrics of water consumption, occupied land area, land use and local air pollutants emissions. Turney and Fthenakis (2011) established four dimensions of local environmental impact that consisted of (1) land use, (2) human health and well-being, (3) wildlife and habitat and (4) geohydrological resources. Impacts on these dimensions were evaluated based on a comparison, along several metrics, between solar PV electricity generation and traditional thermal generation.

Previous works have approached the impact on the local environment of energy systems through the well-established EIA approach as well as the more comprehensive SEA approach (Bérubé and Cusson, 2002; Jay, 2010). These approaches include detailed reviews of individual project proposals are beneficial for singular project planning activities, however may be too comprehensive and arduous for a large national EP activity before the project specificities have been detailed.

For the current work the environmental impacts on the local environment consist of those resulting from the installation and use of electricity generation technologies. The dimensions considered in local environmental impacts include the impact on air, water, and land quality.

3.6.7.1 Attribute - Minimize impact of the energy system on the local environment

In the absence of a comprehensive natural or proxy attribute, which evaluates all of the impacts of concern, a constructed scale attribute with defined levels is employed. The attribute evaluates the local environmental impact of the electricity generation system as a proxy of the FE system. The current model was not constructed to conduct a detailed evaluation of environmental impacts, but to allow for the comparison of relative environmental impacts between multiple alternatives. A constructed attribute allowing for evaluation along multiple dimensions of local environmental impacts is suitable for this.

A defined levels constructed scale consisting of four distinct levels was developed for the current work. Each level is defined by an appropriate description of local environmental impact by three criteria; air quality, water quality, and land quality for installation operation and maintenance of electricity generation technologies.

The impact on air quality is established based on assumed emission of air pollutants of concern, namely the commonly employed metrics of NO_2, SO_X and particulate matter (Curci et al., 2012; Diakoulaki and Karangelis, 2007; OECD, 2008, 1993; Rovere et al., 2010; Torchio et al., 2009).

The water quality impact is evaluated based on the assumed withdrawal of water, the consumption of water, and affluent discharge in to natural water ways (OECD, 1993; IAEA, 2005; EPA Ghana, 2007; Feeley Iii et al., 2008; Rovere et al., 2010).

The land quality impact is evaluated on deforestation, transformation of land, and the length of occupation (OECD, 1993; Afgan and Carvalho, 2002; Jay, 2010; Rovere et al., 2010; Turney and Fthenakis, 2011; Ribeiro et al., 2013).

The installed capacity [MW] is a reasonable proxy for the measure of the impact on the local environmental impact on air, land and water quality that an electricity generation technology has.

The evaluation of the defined levels is rigid and all criteria have the same weight so that evaluation of the impact on one criteria (e.g. land) may decide the attribute level evaluated despite no or negligible impacts in the remaining criteria. The defined levels are presented in Table 3-17, and it is seen that lower values on the scale are more desirable than higher ones.

There are limitations to the approach used here. The constructed scale of local environmental impact is a qualitative scale in which the numbers 0, 1, 2, and 3 were assigned arbitrarily. Also within the weighted sum method the difference from 0 to 1 is assumed to be equal to the difference from 1 to 2 and etc., which may not be consistent with actual differences. Granted that these limitations exist, there was a need for a simple synthetic indicator for the current work. Additionally, care was taken to explicitly define each level 0, 1, 2 and 3 ensuring that each would represent similar value differences. The defined levels and the approach should of course be discussed with DMs in further applications to ensure their applicability.

For the case study generic electricity generation plants are considered, and each generation technology type is assigned a local environmental level, based on information available on the generation type and expert evaluation. In future cases in which specific generation technologies are to be considered within a planning activity, each individual generation plant can be evaluated separately by the analysts and DMs involved. It is again acknowledged that assigning defined levels to the technologies may be highly subjective to the DM and their preferences; however, this could be done within a conference environment allowing for discussion and compromise. A sensitivity analysis conducted in the current work will also evaluate alternative evaluations. The local environmental impact levels are presented in Table 3-18, for generic generation types.

A weighted sum method is used where the local environmental impact is equal to the product of the weights of each technology in the electricity generation scheme, w, and their evaluated level of impact, L. It is acknowledged that the weighted sum is an approximation as it considers the installed generation technology and not the capacity actually used, and the former may be larger than the latter.

$$Local\ Env.Impact_y = \sum_{u=1}^{W} w_{u,y} \times L_u^E \quad [-] \qquad \textbf{Eq. 3-21}$$

$$\sum_u w_u = 1\ and\ 0 \le\ w_u\ \le 1\ for\ all\ u = 1,2,3,\dots Y$$

Where:

$w_{u,y}$: Share that the technology represented in the total installed capacity of electricity generation technologies in year *y* for all installed capacity generation technologies *u=1, 2, 3, …, Y* [%]

L_u^E: Evaluated level of local environmental impact (*E*) of the generation technology type [-]

Table 3-17 - Defined levels of constructed scale of impact on local environment

Attribute level	Representative local environmental impact
0	**No or negligible impact to:** Air quality: No or negligible emissions of air pollutants of concern.
	Water quality: No or negligible water withdrawal, water consumption, and negligible pollutant discharge.
	Land quality: No or negligible deforestation and no or negligible land area transformation or time period of occupation.
1	**Minor negative impact to:** Air quality: Minimal emissions of air pollutants of concern.
	Water quality: Minimal water withdrawal as well as minimal or no pollutant discharge in water.
	Land quality: Minimal deforestation for energy use, minimal transformation of land, and land occupation is short.
2	**Moderate negative impact to local air, water, land quality:** Air quality: Moderate emissions of air pollutants of concern.
	Water quality: Moderate water withdrawal and consumption as well as moderate pollutant discharges in water.
	Land quality: Moderate deforestation rate for energy use, moderate transformation of land that has moderate periods of occupation.
3	**Major negative impact to:** Air quality: Large quantity of emissions of air pollutants of concern.
	Water quality: Large water withdrawal and or consumption as well as significant pollutant discharges.
	Land quality: Unsustainable deforestation rate for production of energy, and there is major transformation of land, with large time period for occupation.

Table 3-18 - Technology environmental impacts -Ghana

Conversion technology	Local Env. Impact level [Table 3-17]	Description
Oil	3	—High emissions of air pollutants of concern. —Moderate withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges, heat and petroleum products, —Moderate transformation of land with moderate period of occupation.
Coal	3	—High emissions of air pollutants of concern. —Moderate withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges, heat and petroleum products, —Moderate transformation of land with moderate period of occupation.
Gas Turbines	2	—Moderate emissions of air pollutants of concern, namely NO_x —Moderate withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges, heat and petroleum products, —Moderate transformation of land with moderate period of occupation.
CCGT	2	See Gas Turbines.
Large hydro	3	—No or negligible local air quality impact. —Major transformation of land for construction and reservoir, transformation is for extended to indefinite period of time. —Moderate to Large withdrawal of water for electricity generation.
Small hydro	0	—No or negligible impact on local air or land quality, —Negligible water withdrawal and land transformation due to dispersed small hydro.
Large Wind-onshore	1	—No or negligible local air or water quality impact. —minor transformation of land due to small footprint of technology, and possibility of continued use of surrounding land.
Large Wind-offshore	1	—No or negligible local air or water quality impact. —Minor transformation of offshore land area and landscape due to small footprint of technology, and possibility of continued use of surrounding land
Small wind	0	—No or negligible local air or water quality impact. —Negligible transformation of land due to small footprint of technology, and possibility of continued use of surrounding land.
Solar PV Plant	1	—No or negligible local air or water quality impact. —Minor transformation of land due to small footprint of technology, and possibility of continued use of surrounding land.
Concentrated Solar Plant	2	—No or negligible local air or water quality impact. —Moderate transformation of land due to large footprint of technology.
Stand-alone Solar (building)	0	—No or negligible local air or water quality impact. —No or negligible transformation of land due to large footprint of technology.
Landfill Biogas	1	—Minimal emissions of air pollutants of concern as only reaching 1 to 3MW by 2020: namely NO_x —Minimal withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges, heat and petroleum products, as only reaching 1 to 3 MW by 2020. —Negligible to minimal transformation of land with minimal period of occupation, as landfill is already present.
Municipal solid wastes	2	—Moderate emissions of air pollutants of concern, namely NO_x, SO_x, mercury compounds, dioxins. —Moderate withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges including but not limited to heat, and petroleum products,

		—Moderate transformation of land with moderate period of occupation.
Biomass and woodwastes[1]	2	—Moderate emissions of air pollutants of concern, namely NO_x, SO_x, mercury compounds, dioxins. —Moderate withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges including but not limited to heat, and petroleum products, —Moderate transformation of land with moderate period of occupation.
Nuclear	3	—No or negligible emissions of air pollutants of concern. —Moderate to high withdrawal and consumption of water resources, for cooling, as well as possibility of moderate pollutant discharges, heat and petroleum products, —Moderate to high transformation of land with high period of occupation. High period of occupation of land for nuclear waste disposal and storage.
Large Solar PV Plant	1	—No or negligible local air or water quality impact. —Minor transformation of land due to small footprint of technology, and possibility of continued use of surrounding land.
Wave Power	0	—No or negligible local air or water quality impact. —No or negligible transformation of land due to large footprint of technology. No or negligible footprint of technology in marine environment in which it is installed. —Negligible withdrawal and consumption of water resources or pollutant discharges
Tidal-range Barrage Power	0	—No or negligible local air or water quality impact. —No or negligible transformation of land due to large footprint of technology. No or negligible footprint of technology in marine environment in which it is installed. —Negligible withdrawal and consumption of water resources or pollutant discharges
Tidal Stream Power	0	—No or negligible local air or water quality impact. —No or negligible transformation of land due to large footprint of technology —Negligible withdrawal and consumption of water resources or pollutant discharges
Hybrid Diesel & Solar Minigrid	1	—Moderate emissions of air pollutants of concern. —Minor transformation of land due to small footprint of technology, and possibility of continued use of surrounding land.

1. Assumed municipal solid waste however biomass is used here.

References: (IEA, 2002; IEA-ETSAP, 2011; Turney and Fthenakis, 2011) & Expert judgment

3.7 Energy modeling

A national energy systems model for the country of the case study was required in this work specifically to evaluate a reference "business as usual" projection and constructed policy alternatives in achievement of the EP objectives. For this, the primary outputs of the model were the data requirements for the evaluation of each alternative through the quantifiable attributes detailed in the previous section.

The energy model is further detailed in Chapter 4. The key parameters of the future scenarios as well as alternatives modeled are presented with Part I of the case study in Chapter 5.

3.7.1 Elaboration of possible future scenarios

A coherent systematic evaluation of EP alternatives is achieved through the construction of a single model for the case study country that is used the projection and evaluation of the constructed EP policy alternatives within a common future *scenario*. The alternatives were constructed within a *scenario*, that is not within the control of the user. *Scenarios* are the considerations that are based on factors outside the scope of the modeler but are relevant to the future situations (Finnveden et al., 2003).

3.7.2 Development of a reference projection

A *forecast* or *projection* provides information about possible future situations (Finnveden et al., 2003). The *reference projection* was forecasted to evaluate the performances on the attributes within a "business as usual" future. This will allow for a base case in which to compare constructed policy *alternatives*.

3.8 Development of EP alternatives

An *alternative* here is a set of actions constructed by the modeler, that results in a future that reflects different outcomes as compared to the base-case (Finnveden et al., 2003).

The *alternatives* for this work will represent comprehensive energy policy alternatives for the case study country. *Alternatives* will be pre-constructed for evaluation within the MCDA model chosen.

The constructed *alternatives* attempted to express the extremes within the decision space of energy policy options. This provided DMs and stakeholders with an understanding of the outcome of different policy strategies.

3.8.1 Methods of EP alternative generation

As stated by Neves (2012) an adequate and disparate set of EP alternatives is essential to the EP activity. An adequate number of alternatives allows for representation of as much of the decision space as possible within a succinct set which is manageable by DMs and stakeholders within an analysis framework. Disparity is important to ensure that the alternatives explore a sufficient amount of the decision space as described by the dimensions set in the structuring of the problem (Zeleny, 1982).

The work followed in what Neves (2012) referred to as a *tailor-made* approach. Constructed alternatives for national EP consist of a diverse mix of actions ranging from interventions on the demand to the supply side of the energy system. These actions must be selected based on specificities of the specific energy system under analysis. The reason for this is that actions taken in one context may not be appropriate or have a minimal affect within the context of a different national EP activity.

Alternatives were constructed prior to interaction with DMs and stakeholders, in this work, to ensure that a diverse set of alternatives was available for evaluation.

3.9 Multi-criteria decision support methods

An appraisal tool was required within the decision support methodology to allow for evaluation of EP alternatives in achievement of EP objectives.

The EP activity must account for several decision making criteria corresponding to different objectives that are often contradictory including economic, environmental, and reality (e.g. technology availability) aspects (Logan and James, 2009; Bouvy et al., 2010). In the planning stage DMs are required to choose among alternatives and make tradeoffs among objectives. Multi Criteria Decision Aid (MCDA) methods were designed to improve the quality of decisions that DMs are required to make and aid in structuring the decision process. MCDA models also encourage DMs to reflect on decisions, aid DMs in making consistent and rational evaluations of risk and uncertainty, facilitate negotiation among DMs, and finally make decisions more transparent requiring the process to be documented (Hobbs and Meier, 2003).

3.9.1 Classification of multi-criteria decision support methods

MCDA methods can be divided into multi-objective decision making (MODM) and multi-attribute decision making (MADM). MADM methods start with a finite set of alternatives, which are explicitly known prior to the process, while MODM methods do not have predetermined alternatives and start with a set of objective functions and constraints establishing feasible solutions (Pohekar and Ramachandran, 2004; Haydt, 2012). There are multiple approaches to further classification of MADM methods of MCDA. Belton and Stewart (2002) presented a scheme that separated the methods into three schools of thought, specifically value measurement models, goal aspirations and reference level models and finally outranking methods (also referred to as the European/French school). A brief description of these models is presented.

The value measurement models assign a quantitative score to each alternative based on partial weights assigned to the criteria by the DMs indicating willingness for tradeoff between criteria (Belton and Stewart, 2002). Methods that fall into this category include the analytical hierarchical process (AHP) from Saaty (1980) as well as the multi-attribute value theory (MAVT) of which multi-attribute utility theory (MAUT), from Keeney and Raiffa (1976), is said to be an extension of and a more rigorous approach incorporating risk preferences and uncertainties (Saaty, 1980; Løken, 2007a, 2007b). The goal aspirations and reference level methods are often referred to as goal programming methods. This category of methods works to find alternatives that come closest to achieving a predetermined aspiration level (Belton and Stewart 2002). The outranking methods conduct a pair by pair comparison to determine which alternative is preferred in relation to each criteria and then aggregate all the preferential comparisons of criteria to determine an outranking relation on the alternatives. Two main examples of the outranking methods are the ELimination & Choice Expressing Reality (ELECTRE) and Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHE) method (Benayoun et al., 1966; Roy, 1985; Brans, 1982; Brans and Mareschal, 2005).

3.9.2 Value measurement methods and software

The value measurement methods assign a quantitative score to each alternative based on the performance in each criteria and partial weights assigned by DMs. The weights assigned indicate DMs' willingness for tradeoff between criteria, and not the importance of the respective objective (Keeney, 1992).

3.9.2.1 Multiattribute utility theory

MAUT methods fall into this category and are for use in problems with discrete sets of alternatives. In MAUT a preference function assigns values to alternatives in their achievement of objectives in accordance with the preferences of the DMs.

Where preference functions are established under certainty they are referred to as value functions. DMs first establish partial value functions, $u_j(g_{ij})$ that describe the preferences regarding the performance, g_{ij}, on the alternative i for the attribute j. This allows for evaluation of the relative strength of preference for each criteria. An example is shown in Figure 3-6 for a generic objective to minimize cost with two alternatives in a partial (or marginal) value function. Partial value functions are required to translate the performances into values that can be combined with weights into a value function. The relative scales are anchored on their ends by the worst and best performance on the attribute respectively. Where a value of zero is assigned to the least preferred alternative performance and one the most preferred.

These partial value functions are then used to convert the performances of an alternative into value scores or partial utilities. Weights are assigned to the attributes corresponding to each objective allowing for the calculation of an overall value score from the scores of the partial value functions (Dyer, 2005).

When uncertainty about future outcomes of decision problems exists utility functions can be established and used in the place of value functions. The utility functions allow for inclusion of the DMs' attitudes towards risk in the preference function (Dyer, 2005), but value functions are often used in place of the utility functions due to the complex nature of the elicitation process that the latter requires of DMs (Montibeller, 2005).

The overall score of preference functions in MAUT can be assessed through preference functions of different forms (e.g. additive or multiplicative) depending on the DMs' preferences. Where the DM's preferences satisfy the condition of mutual preferential independence an additive form can be used (Dyer, 2005). This condition requires that every subset of attributes is preferentially independent of its complement (Belton and Stewart, 2002). This indicates that the preferences associated with the consequences of the alternatives on one subset of attributes (e.g. trade-offs) are independent from the level that the alternatives have on the remaining attributes, assuming the latter are kept unchanged.

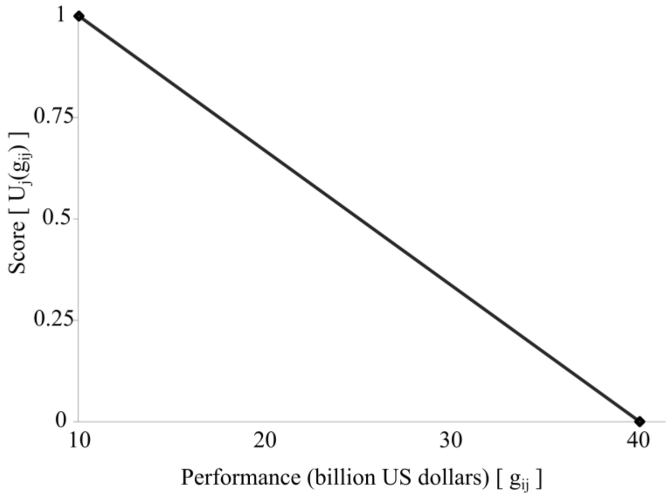

Figure 3-6 – Example of performances and corresponding partial utilities for the attribute of cost

The additive form of a preference function is a compensatory preference function model in that it allows for a low performance in one criteria to be compensated for by higher performances in other criteria. The linear additive representation is the most common approach and is shown below in Eq. 3-22.

$$V(a_i, k) = \sum_{j=1}^{n} k_j u_j(g_{ij}) \qquad \textbf{Eq. 3-22}$$

Where:

$k = (k_1 \dots k_n)$: Importance parameters, where all k_j are non-negative and $\sum_{j=1}^{n} k_j = 1$.

u_j : Partial value function for the attribute j.

g_{ij}: Performance element *i* of alternative a_i corresponding to the attribute j.

The MAUT methods do not admit incomparability as alternatives either have the same value (or utility) or an alternative has a higher value (or utility) than the other.

The benefits of the actual MAUT process for the DMs were emphasized by Buehring et al. (1978). The process of assessing utility functions was claimed to aid DMs in filtering out the most important issues in a decision problem.

Concerns about the MAUT process center on the difficulties presented to DMs in its use. Particular difficulties exist in the assessment of probabilities and the assignment of utilities to the criteria, as these activities may present complications to DMs who often do not have a clear perception of their own risk preferences (Løken, 2007b; Siskos and Hubert, 1983).

3.9.2.2 Analytical Hierarchy Process

The analytical hierarchical process (AHP) from Saaty (1980) is similar to the MAUT methods as it also uses a linearly additive preference model that determines an overall score for each alternative providing a cardinal ranking. The assumptions for the value measurements, the methods in which DM judgments are ascertained, and the methods of transforming these into the overall quantitative score are essentially different (Belton and Stewart, 2002).

AHP consists of a process of establishing weights for a given set of criteria through subjective assessments of the importance of these criteria. The process is conducted through pairwise relative comparisons of criteria asking the DMs questions “how important is criterion i relative to criterion b?”

AHP has also been the subject of debate in the field of MCDA, and the rank reversal problem is one of the often cited concerns of the process (DCLG, 2009). The introduction of a new alternative can affect the relative ranking of the original alternatives, while the performance ranges of the attributes remain unchanged. Concerns exist regarding certain theoretical foundations on which AHP is based (Belton and Gear, 1983; Bana e Costa and Vansnick, 2008).

3.9.2.3 MACBETH

The Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) was developed out of concerns regarding the potential disadvantages of the intensive cognitive demand placed on DMs in the development of values scales in MCDA methods. Numerical and non-numerical techniques to develop values scales alike require DMs to perform unnatural cognitive tasks that could result in substantively meaningless outcomes. MACBETH was therefore developed to provide a method that allows for the construction of a quantitative value scale allowing DMs to make only qualitative judgments of difference of attractiveness. Allowing DMs to make qualitative judgments of attractiveness between two elements at a time, MACBETH does not force DMs to produce direct numerical representations of their preferences (Bana e Costa et al., 2005; Montibeller, 2005).

As the method develops a quantitative model of values, which can be used to calculate the attractiveness of alternatives (through an additive model) and provide ordinal ranking of attractiveness, it is similar in structure to other MAUT methodologies, but differs in the elicitation of the value scales from DMs.

First, DMs need to interactively make qualitative judgments about the performance of the alternatives separately for each of the criteria considered to build value scales. Following this, a similar process to develop weights for the criteria is undertaken. The model then checks these judgments for consistency before constructing a quantitative model where scores are calculated for the alternatives that are consistent with the DMs judgments (Bana e Costa et al., 2005).

The method has recently been applied within the EP activity (Burton and Hubacek, 2007; Neves, 2012; Neves et al., 2015).

3.9.2.4 VIP Analysis

VIP Analysis (Variable Interdependent Parameters Analysis) is a MCDA support system developed for choice problems where DMs are unable or unwilling to fix precise values for the importance parameters of an additive value function (Dias and Climaco, 2000). Imprecise information can be used for the importance parameters corresponding to the attributes. Acceptable inputs, entered into VIP Analysis as linear constraints, include ranking of importance parameters and limits to value trade-offs.

VIP Analysis calculates the range of results, minimum to maximum value, that are compatible with the imprecise information provided and establishes robust conclusions, which are true for all possible sets of importance parameter values (Clímaco et al., 2009). The maximum regret, or maximum possible disadvantage, which an alternative can have when compared to the remaining alternatives is also evaluated. Dominated alternatives are identified and can be filtered out.

3.9.2.5 SMAA methods

SMAA (Stochastic Multi-Criteria Acceptability Analysis) methods, a family of methods applicable to all MCDA problem types, were developed for use in problems with uncertain, imprecise, and partially (incomplete) information about importance parameters, k, attribute performances, g_{ij}, or other technical parameters of the model (Tervonen and Lahdelma, 2007; Tervonen, 2014). SMAA-2 is a specific method developed for use in ranking problems and is based on a linear additive function (Tervonen and Figueira, 2008).

SMAA-2 methods, within JSMAA (Java implementation of SMAA), can be used to evaluate the acceptability of the alternatives given unknown or partial information regarding the importance parameters. The SMAA-2 methodology employed in the JSMAA software is described in detail by Tervonen (2014). The basic idea of the SMAA-2 methodology is to draw randomly many parameter vectors and to present statistics for the results corresponding to the drawn vectors.

The first of the two main results from SMAA-2 are the Rank Acceptability Factors. These are the share of possible importance parameter value combinations that grant each alternative a specific ranking. The second are the central Weight Vectors. These present the importance parameters, in vector form, that a DM might assign in support of this alternative making it the preferred one. These allow for a form of reverse MCDA activity in which DMs are informed about the type of preference information that would result in specific alternatives being preferred.

The holistic acceptability index provides an evaluation of the overall acceptability of the alternatives and is calculated as the weighted sum of the rank acceptabilities. Sorting of the alternatives by this holistic index allows for grouping of similar alternatives and a more descriptive rank acceptability index. The holistic acceptability index, and resulting holistic ranking, is not intended to provide an absolute ranking of alternatives, as the selection of meta-weights is subjective and may provide different results (Kangas et al., 2006).

Lahdelma and Salminen (2001) suggested three possible approaches to setting the meta-weights. These consisted of *linear weights*, *inverse weights* or *centroid weights*. *Linear weights* give more weight to the middle ranks while *inverse* and *centroid weights* emphasize the best ranks. The *inverse weights* approach is not sensitive to the order of the worst ranks. The *centroid weights* emphasize the higher ranks. Kangas et al. (2006) employed the *centroid meta-weights* for the holistic acceptability index that emphasizes the higher rankings.

3.9.2.6 GRIP

The Generalized Regression with Intensities of Preference (GRIP) from Figueira et al. (2009) allows for the development of a value function with only partial preference information. GRIP follows the MAVT methodology with additive value functions. The GRIP methodology is flexible in terms of the input information required and provides a ranking of alternatives in order of preferences as an output.

Inputs can consist of either (1) a partial preorder of the evaluated alternatives through comprehensive comparisons, (2) a partial preorder of alternatives with analogous comprehensive comparisons of pairs of alternatives, or (3) a partial preorder of pairs of alternatives based on performance on specific criteria subsets (partial comparisons). Preferences can be assigned by pre-defined degrees of intensity of preference, "moderate" "very strong", etc. (Figueira et al., 2009).

The assignment of weights is not required. The method distinguishes the necessary and possible consequences of using all the value functions compatible with preference information provided. This provides a type of robustness analysis in finding all these consequences instead of a "best fit" value function (Figueira et al., 2009).

The GRIP software is available as a plugin to the Decision-Deck (D2) platform initiative; however, D2 is no longer in active development and not compatible with the latest version of Microsoft Windows. Activities have moved to the Decision-Deck D3 online platform and more recently the diviz platform (Decision Deck, 2013).

3.9.2.7 VISA

The Visual Interactive Sensitivity Analysis (VISA) software for multi-criteria decision support from Belton and Vickers (1990) follows a MAVT approach with additive value functions.

VISA establishes the value function in a flexible manner allowing for qualitative weight assignment or elicitation through a SWING weighting method. The software package includes a visually interactive environment that is supportive of an interactive DC.

3.9.2.8 WINPRE

The Workbench for INteractive PREference Programming (WINPRE) (Salo and Hämäläinen, 1995) is a platform that follows a methodology based on MAVT with additive value functions. The software supports evaluations, and choice, of preferred alternatives.

The software is flexible and allows for partial preference information from DMs. Elicitation of weights is done through Simple Multiattribute Rating Technique (SMART), SWING weighting methods, Preference Assessment By Imprecise Ratio Statements (PAIRS), and preference programming. Alternatives can be scored on performance intervals for the attributes (Mustajoki et al., 2005).

The software provides overall value intervals for the alternatives and possible dominance relations given the established constraints.

3.9.3 Outranking

Outranking methodologies are typically applied to problems with discrete options. These methodologies were developed to eliminate options that are considered dominated. Dominance within outranking methodologies is evaluated through weights which assign more influence to certain criteria than others.

The output of outranking methodologies is not a value for each of the alternatives evaluated but an outranking relation (S) between pairs of the alternatives. Here an alternative *a* is said to outrank *b* alternative (*a*S*b*) if there is sufficient conclusion that *a* is at least as good as *b* with no strong argument to the contrary (Belton and Stewart, 2002; Figueira et al., 2005).

The outranking methods conduct a pair by pair comparison to determine which alternative is preferred in relation to each criteria and then aggregate all the preferential comparisons of criteria to determine an outranking of the alternatives. Two main examples of the outranking methods are the ELECTRE family and PROMETHE method (Løken, 2007b).

In outranking methods an option is found to outrank another option if it outperforms another in a sufficient number of criteria of significant importance and is not outperformed by the other option with a large disadvantage on any one criteria. Weights assigned to the criteria within the outranking methods signify the importance of the criteria and not trade-offs, or substitution rates, between criteria as in value measurement methods. The weights represent the influence that the criteria has when it contributes to the majority that is in favor of outranking. The weight is not connected to the range, or the type, of value scale for which the criteria is evaluated on. The alternatives are evaluated on the number of criteria for which an alternative outperforms another and not the relative difference between the performances of each alternative on the criteria.

The outranking methods are, in this sense, considered to be non-compensatory. These methodologies do not use an additive formula in which poor performance in certain criteria can be compensated for by strong performances in other criteria.

The main criticism regarding outranking techniques centers around what have been considered arbitrary definitions of what constitutes outranking and the setting of threshold values (DCLG, 2009).

Outranking methods do possibly capture some of the reality of political decision making by downgrading an option that performs poorly on any specific criteria. As it is assumed that due to poor performance in a specific area of concern would make it difficult to implement the option (DCLG, 2009).

The use of outranking methods in DC situations has been criticized due to their complex methods of aggregating information that may complicate the transparency of the procedure for DMs. Also the inputs that consist of concordance and discordance threshold levels, preference and veto thresholds (of ELECTRE), and the preference functions (of Promethee) have their limitations as they are non-intuitive and not natural cognitive tasks (Belton and Stewart, 2002; Bana e Costa et al., 2005).

3.10 Choice of multi-criteria evaluation method(s)

3.10.1 Requirements of method

The choice of an MCDA method, according to (Roy and Słowiński, 2013), requires the consideration of multiple criteria in-itself. First is the validity of the method for the application, meaning that it measures what is meant to be measured, as different methods can provide different results. Secondly, the method must be appropriate, providing DMs with all the pertinent information for the activity and be compatible with the available data. Finally, the method must be transparent and easy to use, as participants in any activity using the model may not trust the results of a method that they do not understand and perceive as a black box.

In the analysis of a decision problem and selection of an applicable method one of the initial questions to be answered has to do with the type of problem that is to be addressed. Roy (1996) proposed four categories of methods that address MCDA problems, also known as *problematics*. These four problematics where MCDA could be applicable consisted of:

1. Choice - the choice of a single preferred alternative from a set of alternatives.
2. Sorting – insertion of alternatives in predefined homogenous groups with a corresponding preference order.
3. Ranking – placing alternatives in order from best to worst.
4. Description – describing alternatives based on their most distinctive features.

Chen (2006) presented an illustrated adaptation of the classifications from Roy (1996) that was adapted from Doumpos and Zopounidis (2002) as shown in Figure 3-7.

How alternatives will be constructed and how many will be analyzed in a decision problem is an additional key initial question to be answered when choosing a MCDA method (DCLG, 2009).

The aim of the current research is to evaluate the influence that the inclusion of geographical context specific EP objectives may have on outcomes and future energy policy recommendations. The national EP activity in the context of the current work is based on the analysis of complete predefined constructed alternatives. A discrete set of alternatives representing distinct energy policy options will be constructed and evaluated. The performance of these alternatives is to be evaluated through quantifiable attributes in achievement of the objectives in comparison to the reference alternative.

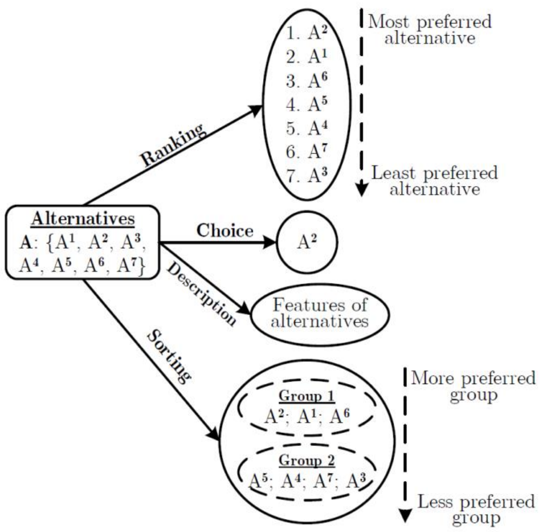

Figure 3-7 – Classification of MCDA problematics - (Chen, 2006)

The most preferred alternative could be ascertained from either a MCDA choice methodology or a ranking of alternatives methodology. A choice methodology will provide a single winner, but a ranking methodology will allow for DMs to either choose the most attractive alternative or see the ranking of other alternatives of possible interest. A ranking will also allow DMs a better understanding of how preference information and the performance of alternatives results in different rankings allowing them the option to use this information in the construction of a new possibly enhanced alternative to add to the evaluation in further stages.

The EP objectives are evaluated by a set of incommensurable quantifiable attributes. This set is comprised of natural, constructed and proxy attributes. These have to be aggregated in some fashion by the evaluation model to provide an overall value to each alternative and to choose the preferred alternative or rank the alternatives.

A methodology that is compensatory and allows for trade-offs between the multiple possibly conflicting objectives of the problem would be preferable. In the case where a non-compensatory objective is considered within a compensatory preference model a possibility is to pre-screen all the alternatives to ensure that they meet the requirements or threshold identified for the specific objective prior to the analysis. This may be the case for the objective of access of the population to FE access.

Three separate sets of EP objectives and corresponding quantifiable attributes (i.e. ECOWAS+, ECOWAS, and Developed Countries), will be used in the evaluation of alternatives. The evaluation model developed in the DC should be a reusable model, deployable for similar evaluations conducted with additional alternatives that may be constructed and evaluated post-DC. The model should preferably allow for the construction of an evaluation model within the framework of one EP objective set (ECOWAS+) and be adaptable with some changes to evaluate EP alternatives within the two additional EP objective sets (ECOWAS and Developed Countries) to be examined with comparable results. This will allow for the evaluation of alternatives through the lenses of different EP objective sets as well as interest groups by allowing for the ability to adjust the weighting of attributes post-DC.

The MCDA methodology employed will be used together with DMs to evaluate alternatives within an interactive DC setting. In order to include the input from different interest groups in the EP activity DMs will be invited to a DC setting where the EP activity will be discussed and the EP objectives and attributes applied to construct a multi-criteria evaluation model to evaluate the constructed policy alternatives. The MCDA methodology in this case should therefore have a transparent methodology which can be easily understood and used with DMs. A visual aid would be beneficial in interacting with DMs that guides, details and presents results from the process. A software tool that employs the MCDA methodology is therefore preferable.

It would be beneficial for the current work to develop a contingency plan for the DC and MCDA evaluation. The application of the MCDA model in evaluation of the EP alternatives has been planned to be conducted within a DC setting together with DMs and stakeholders. It is acknowledged, however that the participants have busy schedules and may be occupied or unable to participate. In addition, the DC is to be held abroad as part of a field study, in which the analyst and author might, due to forces outside of his/her control, not be able to be present and host the conference.

The requirements in a MCDA method are presented together with justification in Table 3-19.

Table 3-19 – Requirements for MCDA method

Requirements of MCDA method	Justification
Allows for evaluation of a discrete set of predefined alternatives.	A discrete set of alternatives will be constructed and evaluated in achievement of objectives compared to the Reference Alterative.
Ability to adjust weighting of attributes (possibly post DC).	Achievement of objectives can be assessed through the lenses of different preferences.
Allows for evaluation of alternatives in achievement of separate sets of objectives and corresponding attributes.	The preferred alternative will be evaluated within each of the 3 EP objective sets, ECOWAS+, ECOWAS & Developed.
Provides a reusable framework for evaluation of alternatives.	Preference scales for value scoring as well as weighting of attributes can be made and applied following the DC to additional alternatives.
Allows for incommensurable quantitative attributes	The attributes consist of natural, proxy & constructed attributes.
Does not require direct numerical representation of preferences from DMs.	Establishing preference information is difficult and DMs may not know or be unwilling to establish concrete weights.
Transparent and easy to use with DMs in DC setting.	Allows for interaction with DMs possibly within a DC event. Software that provides a visual aid would be beneficial.

3.10.2 Selection of MCDA method

The methodology to be followed in the application of the Multi-criteria evaluation of the EP alternatives is detailed in the sections that follow. The sections provide a structure to discuss the methodologies to be employed for each of the separate components. This will also provide a structure for the application of the methodology within the Part II of the case study in Chapter 6.

3.10.2.1 Decision conference

Decision Conferencing as described by Phillips (2007) presents a structure for bringing together the key players who represent the main perspectives on an issue as well as DMs within organizations or groups to facilitate the structuring of problems. Through a DC the objectives, attributes, and finally the results from the multicriteria methods can be verified and the most preferred option can be chosen by DMs. The conference allows for participants to discuss important issues including the objectives of the activity, the building and immediate and continuous display and discussion of models, and the interactive and iterative group activity of reviewing the results of the model (Phillips 2007). The DC brings together a facilitator as well as DMs in one space to structure and review problems together, such as EP problems.

Montibeller (2005) describes the MAVT School of methods as being appropriate for applications where interaction with the DMs within a DC framework is conducted. The MAVT method provides an easier to use and more transparent approach for the participants than other approaches such as the outranking method.

3.10.2.2 Assessing the performance of alternatives

The alternatives in the current work were to be constructed prior to the DC within the energy modeling and development of EP alternatives phase. The alternatives were to be evaluated for their performance on each of the attributes. This pre-established performance matrix would then be an input to the DC activities.

The performance matrix was to be presented to participants to confirm (1) the set of alternatives were appropriate, and (2) that participants agreed to continue with the established performances. In the case that participants did not agree, additional alternatives and performances could be established in the follow-up to the DC.

3.10.2.3 Aggregation of multi-criteria performances

The current work, which evaluated a discrete set of EP alternatives, falls in the category in which MADM methods are applicable. Table 3-20 below presents a review of potentially applicable methods.

Table 3-20 – Evaluation of applicability of MCDA methods

Requirements for MCDA method	MAUT	MAVT	ELECTRE	PROMETHEE
Allows for evaluation of a discrete set of predefined alternatives.	+	+	+	+
Ability to adjust trade-offs of attributes (possibly post DC).	+	+		
Allows for evaluation of alternatives in achievement of separate sets of objectives and corresponding attributes.	+	+	+	+
Provides a reusable framework for evaluation of alternatives.	+	+	+	+
Allows for incommensurable quantitative attributes	+	+	+	+
Does not require direct numerical representation of preferences from DMs.		+ *multiple methods*	+ *ELECTRE TRI*	
Transparent and easy to use with DMs in DC setting.		+	-	-

“ + ” more applicable
“ - ” less applicable
“   ” not applicable

The outranking methodologies appear to be less applicable in the current work due to their non-compensatory preference function models in which weighting of attributes dictates importance and not trade-offs (Figueira et al., 2005).

The value measurement methods, which include MAUT and MAVT, fulfill largest number of the specified criteria. Trade-offs between the objectives in evaluation of alternatives can be made (Dyer, 2005). Applicability to problems where alternatives are evaluated on their difference in performance in criteria from other (reference) alternatives (Neves, 2012). These methods also provide for a possibly reusable framework for evaluation of alternatives (Bana e Costa et al., 2008).

3.10.2.4 Generating preference information

Establishing precise values for the importance parameters can be difficult for multiple reasons. The values reflect judgment of multiple, possibly disagreeing DMs. It can be difficult to elicit this information in a precise form from DMs. Additionally preferences, and in turn, the values may evolve over time (Dias and Clímaco, 2004).

The preference information necessary for the MCDA methods employed by the software tools used in this EP exercise could be provided in an imprecise form. Precise weights for the importance parameters were not required, only a ranking of these weights.

A method of swing weight “ranking” based on that presented by Converse (2015) was conducted with participants to establish a preferential order ranking of the EP objectives. The method consisted of establishing a benchmark case with all objectives at their worst level [0], and a set of others where each has only one attribute ‘swung’ to its best level [1]. The steps for interaction with the participants consisted of:

Step 1. Identify the worst “benchmark” case & the best case for each objective. [0-1]

Step 2. Establish Ranks: Compare a series of alternative cases in which one objective at a time is set to its best value [1].

Step 2.1. Participants asked “If just one of the attributes could be moved to its best level, which would it be?” This case, and corresponding objective, is then ranked 1.

Step 2.2. Repeated until all cases were ranked (benchmark case should have the worst rank).

Mutual independence requires that the performance of the alternatives on any attribute can be assessed and assigned without knowledge of the alternatives’ performance on any of the other attributes (DCLG, 2009). Only after confirming mutual independence with the participants were the partial linear value functions established.

The partial value functions were to be established within the SMAA-2 JSMAA environment, which provides a visual tool for establishment of linear partial value functions. The linear partial value functions were then to be provisionally established prior to the DC and confirmed together with the DMs.

3.10.2.5 Evaluation of overall attractiveness of alternatives

The review of MCDA methodologies presented a set of potentially applicable methods for the current work. Although a number of the methodologies discussed, and possibly others, were applicable to the current work, VIP Analysis was of particular interest for the current work.

VIP Analysis draws robust conclusions which are true for all acceptable value functions allowing for the elimination of (quasi-) dominated alternatives by the DMs. The method provides information to the DMs about how much alternatives are affected by variability of the parameters considered. The evaluation procedure requires DMs to explore the model and the problem through multiple methods improving their ability to make a choice of the most preferred alternative. Also, the VIP Analysis software is suitable for a DC setting.

The SMAA-2 methodology presents an additional tool, which can be employed both as a contingency plan (i.e. cancelling of the DC), and as a supporting tool for analysis of preference information. SMAA-2 was developed for use in situations where attribute values and/or preference information are not known or are imprecise. Use of SMAA-2 with DMs was of interest in this work to evaluate the likelihood that each alternative would have to be the preferred one. Also, the favorable first rank weightings for alternatives provide insight to DMs as to what type of preferences would correspond to different alternatives being preferred and their respective rankings. For the calculation of the holistic acceptability index (Section 3.9.2.5) the current work will follow Kangas et al. (2006) employing the centroid meta-weights that emphasize the best ranks.

3.10.2.6 Sensitivity analysis

The MCDA methods to be used to appraise the alternatives, VIP Analysis and SMAA-2, are based on methodologies that evaluate all weighting possibilities given different constraints. A sensitivity analysis was therefore developed to evaluate alternatives given possible variations in their performances on the attributes.

Chapter 4

National energy system modeling

4.1 Energy systems modeling

Models are built to reasonably represent reality and to simulate the behavior of systems. To accomplish this, simplifications of certain aspects of reality are often required, which in turn may limit a model to specific contexts for application. Energy systems models used in the correct application can provide valuable insight to complex systems. National EP is a complex activity requiring an energy system model to support it.

The current work was an effort to contribute to the advancement of methodologies supporting national EP practices in developing countries. Specifically, the purpose was to support decision making activities in evaluation of EP alternatives within the context of developing countries. One integral piece of the EP activity is the modeling of energy demand and supply as well as the forecasting of these along the planning horizon. This allows for construction and evaluation of multiple EP alternatives in support of the decision making activity and finally energy policy development. A national energy system model was therefore required for the current work.

The current chapter details the requirements and characterization of such a model. The considerations for developing a model fit to the specific application of energy demand and supply modeling are described. The methods for energy demand and supply projections within the planning horizon are also presented.

4.2 Energy model characterization

Numerous classification methods have been presented for energy modeling tools, and reflect the purposes for which the models are being reviewed by the sources. Grubb et al. (1993) used six dimensions to classify models, namely: analytical approach (top-down vs. bottom-up), time horizon, sectoral coverage, optimization versus simulation techniques, level of aggregations and geographic coverage. Hourcade et al. (1996) presented three dimensions for model characterization, namely: purpose of the models, structure, and external assumptions. van Beeck (2003) conducted a review of models based on ten dimensions that consist of: perspective on the future, the specific purpose, the model structure (internal & external assumptions), the analytical approach, the underlying methodology, the mathematical approach, geographical coverage, sectoral coverage, the time horizon, and the data requirements. Bhattacharyya and Timilsina (2009) evaluated models with three overarching themes comprising: theoretical understanding, demand analysis approach, and specific model approach. Within the specific model theme 15 criteria were used, namely: model type (top-down, bottom-up or hybrid), purpose, approach, geographical coverage, sector (activity) coverage, aggregation level, technology coverage, data requirement, skill requirement, versatility (country specific or general), portability to other countries, documentation, capacity to analyze price induced policies, capability to analyze non-price induced policies, rural and traditional energy coverage. Recently Haydt (2012) found little consensus in classification schemes and proposed a structure with eight dimensions, namely: energy carriers considered, model focus, aggregation level, underlying methodology, geographical scale, sectors considered, time horizon, time-scale of energy balance.

From this review a scheme consisting of eight characteristics was used to characterize the EP model. These consist of: purpose of the model, aggregation level, demand analysis level, population types, underlying methodology, geographical scale, time horizon, and finally data requirements.

These characteristics were chosen to provide a clear description of considerations made in selecting an EP model while making an effort to avoid an extensive list with superfluous overlapping information. The criteria that describe energy models are not independent and are often overlapping. As van Beeck (2003) described, the underlying methodology is linked to the analytical and mathematical approach that also have consequences for the structure of the model. In addition, the criteria are of course not an exhaustive list of all characteristics of EP models.

4.2.1 Purpose

The purpose of the energy model refers to the main objective of the energy modeling activity (Bhattacharyya and Timilsina, 2009). Energy sector models have been developed for numerous different purposes, modeling energy demand, supply, or more specific purposes depending on the context for which the model was developed. The modeling purpose may be to evaluate relationships between the energy system and specific evaluations such as impact on the global climate, energy security, or energy access considerations. In this case impact assessments or appraisal models are required to evaluate the different outcomes from energy sector choices (van Beeck, 2003).

Energy demand models focus on the energy demand that may be present at different levels from the global to the local level, or within different sectors. Demand models typically address demand as a function of changes in some activity level such as population or households, income, or energy prices. FE demand is not always disaggregated into separate FE carriers, and often only a single carrier such as electricity is modeled.

Energy supply models are generally built to assist in selecting the PE supply conversion technologies that ensure that FE demand is met. The demand, however, is an input to the model. The technical aspects of conversion technologies, such as electricity generation options, are considered in addition to the financial considerations.

Energy supply-demand models join these two modeling purposes to allow for efforts to balance demand and supply. Generally, demand is forecasted for one or more carrier that then drives a supply side model attempting to meet demand through an evaluation of the PE supply and conversion technologies necessary.

Impact assessment models are those that assess consequences that apply to choices made in the energy sector. Impacts often include financial costs and benefits, but may also have impacts on the economy through employment, health, and the local or global environment.

Appraisal models are constructed to support decision making processes, and to allow for the comparison of a set of EP alternatives based on a predetermined set of attributes. Appraisal models, as well as impact assessment, go a step further then demand and or supply models. Although they work in tandem with these models, they are linked to quantifiable methods to evaluate attributes of considered alternatives.

An example of a model developed for a specific purpose is the National Energy Modeling systems (NEMS) from the United States Department of Energy that was developed to support US energy policy analysis and strategic planning (Kydes et al., 2004; US EIA, 2009). These context specific models are not readily adaptable to new applications.

More general models such as the Markal (market allocation) and TIMES (The Integrated MARKAL-EFOM System) family of energy models were not developed for specific contexts and can be used to develop models for geographic regions, such as national EP, as defined by the modeler. The main output from this family of models is an energy system that is based on supply constraints to meet end-use demand with the least cost option (IEA, 2014d, 2014e). The Long range Energy Alternatives Planning System (LEAP) from the Stockholm Environment Institute is a commonly used, highly flexible, and user friendly model generator and has been used for many different EP applications. The LEAP software also includes considerations for evaluation of alternatives by user defined attributes (COMMEND, 2015).

4.2.2 Aggregation level

The distinction commonly made for the level of aggregation is along the lines of top-down or bottom-up modeling methods. Top-down methods approach modeling systems and technologies from an aggregated data level examining interactions between the energy sector and other sectors of the economy. Bottom-up approaches follow a disaggregated approach that starts from the activity level, end-uses and technologies that manifest energy demand typically with more concentration uniquely on the energy sector. Models can be developed around either aggregation level or employ a mix of methods representing a hybrid of these approaches (Lanza and Bosello, 2004).

Aggregated, top-down analyses of energy demand are often used and can provide valuable information on general issues and trends for energy policy development. The measure of EI or the energy requirements per unit of a driving economic variable is an example of an aggregated analysis (Bhattacharyya, 2011). Aggregated analyses with a macro level view of energy demand, however, do not permit a clear understanding of the specific characteristics of the FE demand sectors of an economy. The demand for various FE services, which drive the demand for FE, are not the same across all the sectors. There are also different sets of end-use technologies that provide these services within each sector and between the different sectors. Some FE services can be met through different FE carriers and end-use technologies interchangeably while other services cannot. Cooking is a FE service that can drive FE demand for fuelwood, charcoal, electricity, LPG, or other carriers. There are also various end-use technologies available to provide this service employing each FE carrier. Examples include cooking with fuelwood on a traditional 3-stone stove or an improved stove, and lighting with a compact fluorescent lamp (CFL) or an incandescent lamp.

A disaggregated sectoral level analysis of FE demand is required in order to capture the different FE services, FE carrier demand, and end-use technologies employed within the various economic sectors. The disaggregated approach is of use in EP exercises as it allows for formulation of alternatives that include specific sector level interventions such as DSM activities, promotion of specific technologies, and shifting between different FE carriers, among other others (Bhattacharyya, 2011).

The more disaggregated approach (also referred to in literature as engineering-economy or end-use models) offers many benefits for EP. Methods following this approach allow for modeling of individual processes and technologies involved in the conversion and use of energy. They also allow for the capture of structural changes and technological developments as they allow for scenario developments by the user and do not rely solely on past historical trends or assumptions regarding future evolutions. The model is then capable of including potential new energy services and their respective energy demand and is not constrained only to the growth of existing demand, as may be the case within areas of developing countries (Bhattacharyya and Timilsina, 2009). In the context of developing countries, they also allow for further disaggregation along urban, rural, and peri-urban divides, and can include informal activities that are not included in more aggregated top-down economic based theories.

The FE demand, within the energy balance, is often broken down into a set of representative sectors allowing for grouping of similar demand categories for FE services. This disaggregation depends on the purpose of the EP activity as well as the availability of data. A common disaggregation is that of six sectors comprising: Residential, Service, Industry, Transport, Agriculture and Fishery, and non-energy use (Bhattacharyya, 2011). Often, due to similarities in the FE demand of the Residential and Service sectors these are combined into a "buildings" sector (IEA, 2010d). In some works Residential, Service, and Agriculture and Fishery sectors are grouped into a cluster called "other" (IEA, 2014f).

Depending on the level of disaggregation required, each sector can be separated into a set of representative subsectors. The Industry sector can be disaggregated into subsectors of manufacturing, mining, and construction. The manufacturing subsector is diverse and includes multiple activities such as food processing, textile work, pulp and paper and various other manufacturing activities. The transportation sector can be broken down into subsectors; however, this is done to separate the modes of transportation such as road, rail, air and water transport. Each of these transport types can then be further disaggregated as required by the model.

4.2.2.1 Demand analysis level

The demand analysis level describes the method with which energy demand consumption is disaggregated and projected. Commend (COMMEND, 2014) proposed two analysis level approaches that consist of variations of a generic activity level analysis, (1) FE demand analysis, and (2) useful energy demand analysis.

Within the generic activity level approach, energy consumption[14] is calculated as the product of both an activity level and the annual EI. This approach is shown in a general form in Eq. 4-1.

$$energy\ consumption = activity\ level\ \times energy\ intensity \qquad \textbf{Eq. 4-1}$$

EI is a measure of the energy requirements per unit of this driving activity level variable. The EI can be expressed at different levels of aggregation in the demand analysis.

[14] Strictly speaking, "energy consumption" referring to the destruction of energy, does not exist, as the first law of thermodynamics states that energy cannot be created or destroyed merely transformed from one form to another. This expression has, however, become a conventional term and it will be used as equivalent to "consumption of energy carriers or resources."

The activity level is the variable assumed to be driving energy demand within the demand sectors. This may be an economic variable, for example GDP or Gross value added (GVA), or other variable specific to the sector (e.g. number of households or mobility). For the productive sectors (i.e. Commercial, Industry and Agriculture and Fishery), the value added at the sectoral level is commonly used as the driving economic variable (Bhattacharyya, 2011). Alternative methods are often employed to measure the activity level driving energy demand in non-productive sectors such as the Residential and Transport sectors.

FE demand in the Residential sector is driven by a number of FE services. While a general set of FE services for the sector can be defined, these services and the FE demand differ due to specificities of the geographic location and climate, income levels of populations, as well as home sizes and household demographics. In the absence of a single measure that drives FE demand in the Residential sector, the number of households is a standard measure of activity in the Residential sector. Use of this measure assumes standard household types and associated FE services.

The transport of goods and passengers is closely linked to economic growth, and GDP is often used as a level of activity in the Transport sector (Bhattacharyya, 2011). This is due to the fact that with increased economic activity and population more demand is placed on the sector to move goods from industry to markets, as well as passengers with the necessity or means to travel. The GDP therefore drives the movement of passengers and freight over a distance and for this reason the mobility measured in passenger-km (pkm) or ton-km (tkm) are also a common measure of activity (IEA, 2010d).

As the name describes, in a FE demand analysis the EI is expressed in terms of the FE demand per unit of activity. Within this approach the FE demand is typically disaggregated into the sectors, subsectors, the FE services and finally the devices by FE carrier (COMMEND, 2014). FE intensity can also be expressed per device. This then allows for consideration of levels of ownership (devices per household). This level of disaggregation allows for modeling and forecasting FE demand at the sector level.

The useful energy demand analysis evaluates the FE demand based on the useful energy needs such as "kWh/m^2 for heating" and assumptions regarding ownership levels and efficiencies of appliances. This allows for consideration of detailed demand-side efficiency improvements and changes in the FE carrier mix that provides for the demanded FE services. Specifically, it allows for analysis of changes of overall demand over time, for example how income levels or building energy standards change energy demand for heating. It also allows for evaluation of the effect of market penetration of different devices and how the FE demand per unit of useful energy needs changes over time due to the energy efficiencies of the technologies used (COMMEND, 2014).

4.2.2.2 Population types

Within the national boundaries of a country, distinct population types can be identified. Unlike in more developed countries, where FE demand from households can be considered more homogenous throughout the different regions, distinct differences exist between FE demand in rural and urban regions in developing countries. These differences, which include the services available to populations, income levels, and FE access options among others, affect the FE demand of populations. Differences exist in quantity as well as quality, as the FE intensity of households and the FE carriers used to provide FE services differ between households of different population types. It is therefore common to model the Residential sector in developing countries as consisting of the multiple sub-sectors of urban and rural populations (Bhattacharyya, 2011).

High population growth rates, as well as increased migration of populations from rural to urban areas have increased the share of urban populations (UN, 2005). Populations in urban areas have often increased at rates that were faster than infrastructure development or urban planning capabilities of the responsible government agencies. This has resulted in creating an urban periphery population in addition to the established urban core population. This peripheral population, despite proximity to the urban center, shares some characteristics with rural populations due to lack of infrastructure, namely: energy access options and income opportunities (Fall et al., 2008). This urban peripheral gap has been observed in African urban areas as well as in the case study country of Ghana (Simon et al., 2004).

The current work will consider three residential population types consisting of the Urban Core (CoreUrban), Urban periphery (PeriUrban) and rural populations as shown in Figure 4-1 together with their estimated shares in total population for the case of Ghana.

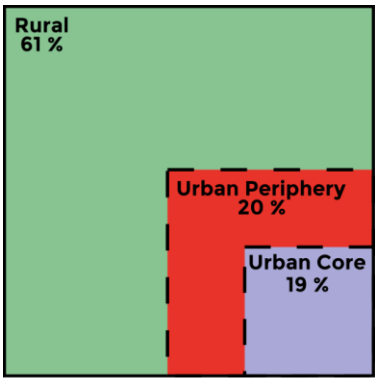

Figure 4-1 - Population types and share of total in Residential sector: Ghana 2008 - *figure by the author* (EC, 2006a; UN-Habitat, 2011)

4.2.3 Underlying methodology

The methodology describes the approach with which the EP activity takes to solve a proposed problem and at times is related to the aggregation level of the model. Van Beeck (2003) summarized the model methodologies from previous literature with seven separate approaches. These consisted of econometric, macro-economic, economic equilibrium, optimization, simulation, backcasting, and multi-criteria methodologies.

Econometric models apply statistical methods, and are based on aggregated data of observed behavior to forecast the future in terms of required inputs (e.g. labor, capital or energy). Early energy demand models were based on econometric methodologies. In demand analysis econometrics do not allow for representation of various conversion technologies. In addition, economic behavior is assumed to be stable as past trends are projected into the future. Econometric models require high quality data as inputs. Within this category are trend analysis or past future extrapolations (van Beeck, 2003). Demand models that base future projections upon past trends are the most common approach as it can be used with highly aggregated data and it is a rather simple approach to use (Bhattacharyya, 2011). In developing countries, emerging energy demand trends may exist, which cannot be forecast based on past demand trends as FE demand may have been previously unfulfilled or suppressed (Bhattacharyya and Timilsina, 2009). Aggregated approaches do not account for structural changes, which may occur in the future, and do not lend themselves well to policy analysis work requiring energy service level data with the purpose of evaluating shifts in FE carriers or end-use technologies used (Bhattacharyya, 2011).

Macro-economic modeling methodologies examine the interaction between economic sectors and the entire economy. For energy modeling, Input-Output tables are often used to describe the energy-economy interactions in terms of transactions between the various sectors. According to van Beeck (2003) these methodologies are useful in exploring different input assumptions or scenarios. Macro-economic methods are not expressly interested in energy, but in the economy as a whole. Like econometric models these methodologies are aggregated approaches that do not allow for representation of specific technologies in the energy system (van Beeck, 2003).

Economic equilibrium models are employed in EP to examine interactions between the energy sector and other sectors of an economy. Economic equilibrium models, similar to macro-economic models, explore interactions between sectors and the economy as a whole. This methodology, however, is used to study interactions in the medium to long-term. Within this work partial equilibrium models examine the interaction between various sectors within the entire economy while general equilibrium models consist of modeling an economy-wide set of equilibriums (van Beeck, 2003).

Optimization models are often used in EP to aid decision making in selecting optimal energy sector investments. This methodology searches for the optimal choice based on a set of incomes and constraints. Often the objective function in these models is to minimize investment costs or environmental impacts. These models are typically constructed with linear programming or integer programming methodologies (van Beeck, 2003).

Simulation models are often used in scenario analysis and consist of a simplified operation of a system to be modeled. These models are considered static if they represent system operation within a specified period only and dynamic if the output of the current period is affected by outputs from previous periods. These are highly flexible tools that allow for construction of various types of energy system models. Simulation models are often flexible software packages or a modeling "tool box" according to the World Bank et al. (1991) which allow for easy manipulation of constructed models (van Beeck, 2003).

The backcasting methodology sets a desired future energy vision and constructs development pathways that set the plans required to reach this vision. This approach has often been used to explore pathways to different desired energy futures (van Beeck, 2003).

Multi-criteria methodology type models, described in more detail in Section 3.9, are related to appraisal models and aid DMs in reviewing and selecting EP alternatives. Models of this type allow DMs to evaluate alternatives with the use of multiple criteria considered pertinent to the EP activity (van Beeck, 2003). The use of multi-criteria methodologies in energy models has become more common and has been employed in various EP activities (Diakoulaki et al., 2005). Models within this category, however, are not typically intrinsically energy models, and therefore are generally used for the evaluation of results generated by other types of models.

4.2.4 Geographical coverage

The geographical coverage of EP activities can be separated into different scales. The local scale focuses on cities, towns or municipalities. The regional scale covers a larger section within a country including multiple towns and municipalities. The national scale consists of an entire country. The regional–international scale includes a number of countries or regions that cross national boundaries. Finally, there is the global scale. Modeling at the global scale is often done for climate modeling purposes as an example.

EP at the local level is typically focused on energy demand modeling as the energy supply considerations often pass local modeling boundaries. This is the case in electricity systems where demand exists locally, however generation and transmission are done at the national level. This is not always the case, however, as minigrids or stand-alone generation systems may fall within the local model boundaries. However, modeling at the local level often requires detailed disaggregated data, and does not allow for modeling of energy interventions for the society as a whole (van Beeck, 2003). Local level interventions also imply some national level policy or strategy that can be implemented at the local level to support national efforts. However, when no national level energy strategy exists multiple interventions at the local level can be taken adhoc, and may possibly be counterproductive to each other.

International modeling efforts take a larger aggregated view of demand and supply. This geographical coverage, while beneficial for global concerns such as PE resources or the global climate, is not beneficial at the national or local level where a more detailed analysis, which covers concerns and visions specific to certain societies and their needs, is required.

Regional-international planning has become more common as energy systems have become less internalized within the boundaries of countries and more international with links to neighboring countries to take advantage of diverse PE supplies. Regional-international modeling requires energy modeling of geographic areas that cross borders. Without the support of national modeling activities within each of the countries, international efforts may have difficulty in accessing data or supporting national energy visions.

National level modeling allows for both supply and demand considerations at the national level. Modeling at the national level does not restrict the activity to modeling a homogeneous society, and considerations can be made to consider different regions or population types. It also allows for actors to develop an understanding of energy demand within all regions of a country supporting future local modeling activities. It also aids in developing national policies that provide a basis for future interactions at the international level.

4.2.5 Time horizon

The time horizon is the period of time considered within the EP activity. It is typically measured in years starting from the base year. Energy plans and policies require time to be implemented. Depending on the activity, or infrastructure to be put in place, the time horizon required can vary. EP activities can have a short horizon (approximately 1-5 years) a medium horizon (approximately 5-20 years) or a long time horizon of 30 years or more.

A medium time horizon permits time for the purchase and installation of infrastructure, which potentially requires a number of years, as in the case for electrical energy systems.

EP activities within the ECOWAS region most commonly consist of mid-range time horizons of 9 to 20 years (Lee and Leal, 2014).

4.2.6 Data requirements

Data availability is an important concern, and selecting a model before ensuring that reliable data exists and is available would be a potential misstep. The data input into any model affects the outputs and overall usefulness of the model for planning activities.

Bhattacharyya and Timilsina (2009) emphasized the importance of this characteristic in developing countries as data, models, and the necessary institutions are often lacking. This results in deficiencies in the capacity for statistical analysis, modeling, and data management. This presents challenges for modeling where detailed data is needed, and so models must be selected together within the context of the specific application. This also has implications for the level of disaggregation of the model.

4.2.7 Requirements for a national energy system model

Modeling the energy systems at the national level requires a tool capable of constructing a baseline energy demand projection. The model must allow for the projection of a number of alternatives set within the storylines of different scenarios. A national energy system model that includes considerations of the PE supply, energy transformation processes, FE demand, demand sectors, and FE services was required for this work. The main outputs of the energy demand and supply model were the data required for the measurement of the quantitative attributes for evaluation of EP alternatives in achievement of the EP objectives presented in Chapter 3.

Additionally, an appraisal tool for evaluation of the outputs of the energy system model would aid within the decision support methodology, as it would allow for the inclusion of DMs in the analysis of the alternatives. It would also increase the transparency of the choices made within the EP activity.

A bottom-up disaggregated approach allowing for analysis at the level of FE services within FE sectors was required of the model constructed. The FE demand in the current work was divided into the representative sectors of the case study country (EC, 2006d). These consisted of the Residential, Commercial, Industry, Transport, and Agriculture and Forestry sectors. These sectors were further separated into representative sub-sectors in an effort to maintain homogeneity in consumption and the FE services that the demand represented. Modeling of FE demand within each sector required different techniques that considered the demand sector and subsectors, FE services provided, and end-use technologies.

The breakdown of the demand sectors and subsectors for the example, of Ghana, in this work is shown in Figure 4-2, where the Residential, Industry and Transport sectors are disaggregated into further subsectors. The Transport sector here is seen to have a further split into passenger and freight transport within each individual subsector.

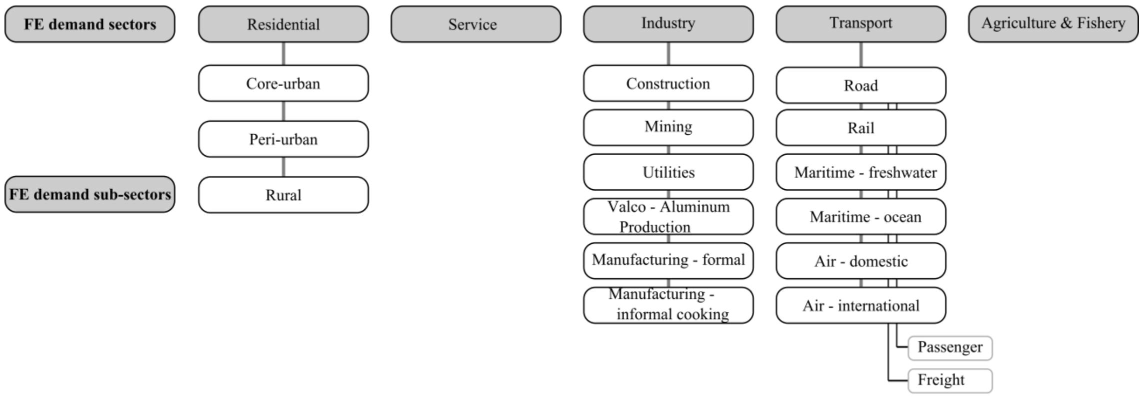

Figure 4-2 - FE demand sectors and subsectors disaggregation: Ghana

The driving activity levels for each of the respective FE demand sectors, considered in the current work, are shown in Table 4-1.

Table 4-1 - Activity level measures for respective FE demand sectors: Ghana

FE demand sector	Activity level measure
Residential	Number of households (HHS)
Service	GVA at sector level
Industry	GVA at sector level
Agriculture & Fishery	GVA at sector level
Transport	Mobility (pkm & tkm)

While the useful energy demand analysis can provide valuable insight it is a more disaggregated approach requiring additional levels of data. In addition, it is more valuable for EP activities focused on detailing demand-side efficiency improvements. The FE demand analysis approach provides a sufficient level of understanding of FE demand in the model and for forecasts of FE demand. The current work began with the FE demand analysis approach and only incorporated a useful energy demand analysis when detailed energy efficiency measures were required (e.g. FE carrier shifts for domestic water heating).

For this work urban areas were represented by the CoreUrban and the PeriUrban subsectors each with different FE demand characteristics. The rural areas were treated as a separate sub-sector. As discussed in the aggregation level section, Section 4.2.2, the disaggregated bottom-up approach would support the modeling of these demand subsectors of the Residential sector.

An energy supply and demand model was required that would permit analysis of specific energy services and the end-use technology mix associated with them within the different energy demand sectors. The current work in developing countries would be best suited by a highly flexible simulation and/or spreadsheet methodology or a hybrid type model of these.

Construction of alternative energy demand and supply policy options and comparison of these with a reference no-plan alternative based on multiple criteria required a MCDA methodology.

The current EP exercise was conducted to support energy policy development for developing countries. In the ECOWAS EP activities at the national level were found to be often absent (Section 2.8). The EP model was therefore constructed for EP at the national scale to support EP at this level.

The most complete data from the SNEP was not for the base year of 2006, but instead for the first year of projection 2008. Data for 2006 was highly aggregated and did not allow for disaggregation to the FE demand sectors or FE services. The data for 2008 was used as the base year in this model to allow for the most complete data set for the base year. The time horizon used in the SNEP from Ghana had a planning horizon of 14 years from 2006 to 2020 (EC, 2006a). In order to have results comparable to the SNEP, 12 years was used as the planning horizon, from 2008 to 2020. The time horizon modeled can be specified by the modeler. Therefore, with additional data for the years beyond 2020, the case study time horizon could be extended or adapted to other base years for future EP activities.

4.2.8 Existing energy systems models

The current work required a model that fulfilled these afore described set of requirements. A review of available energy systems models and software was necessary to identify models that would be applicable. In the case that existing models were judged to be insufficient, given these requirements, an appropriate model would have to be developed.

A large selection of models exists for different EP applications and has been reviewed and classified by multiple authors (Jebaraj and Iniyan, 2006; Suganthi and Samuel, 2012). Pandey (2002) pointed out that the existing models were limited in ability for policy analysis in developing countries due to differences in policy priorities, the dynamics of energy systems and economies of developing countries.

Common software tools, including LEAP, MARKAL, MESSAGE, POLES, have been extensively classified and reviewed in previous works for their applicability in developing countries. A majority of the models and methodologies do not address context-related issues, ignore attributes that are not monetary or quantifiable, are not applicable to developing regions, address technologies as black boxes, neglect small renewable energy systems, and require data that is often difficult to obtain or non-existent (Bhattacharyya and Timilsina, 2010b; Pandey, 2002; Ramachandra, 2009; Urban et al., 2007; van Beeck, 2003).

One of the widely used software packages, Long-range Energy Alternatives Planning (LEAP) was found to have potential for the current work. It provides modeling of energy supply, demand and resource extraction within all sectors of an economy. The model can also be used for calculating and tracking energy related indicators. The tool is a flexible simulation tool allowing users to simulate unique energy systems. The model allows for scenario building and the construction of alternatives for the analysis of different policy considerations in EP activities. The model's accounting type requires low levels of data and does not require high levels of expertise for data input, as do optimization type models. The tool allows for calculation of user constructed attributes calculated with each alternative. These attributes, however, can only be outputs of the model and not inputs, as may be required for energy access concerns. As commercial software, there are built-in calculations that users cannot manipulate or possibly access for increased understanding.

A number of models have been recently developed specifically for EP in developing countries. Reddy et al. (1995) presented a Development-Focused END-Use oriented Service-directed (DEFENDUS) energy demand and supply model. The methodology allows modelers to focus on development goals as well as end-uses in the development of demand alternatives. The methodology is limited to evaluation of environmental impacts, as well as for financial and economic impacts. Ramachandra (2009) presented the Regional Integrated Energy Plan (RIEP) an accounting and simulation tool, designed for the regional and municipal level, for use in evaluating energy policies and developing energy plans. Hiremath et al. (2010) addressed the need for a decentralized energy planning (DEP) method with a bottom-up approach for DEP for a district in India. The DEP method allows for the incorporation of multiple objectives into the model with a goal programming approach. Silva, Herran, and Nakata (2012) developed a linear programming model for decentralized electricity supply considering conversion technologies that use biomass. The model incorporates regional disparities disaggregating areas into urban, rural, and remote areas signifying large cities, areas outside the city with electricity grid interconnection, and areas with no interconnection respectively. Masera et al. (2006) presented the specialized Woodfuel Integrated Supply/Demand Overview Mapping model (WISDOM). WISDOM was developed to fit the need for biomass studies that provide full country coverage based on integration of data at lower geographical scales and detailed graphical information systems (GIS) data.

The flexible modeling tool LEAP was a possible modeling platform for this work. As it is a widely used model it has benefits, as other already existing models may also have. However, specific EP objectives and quantifiable attributes with which compatibility were required to be evaluated within the work which may not have been supported by LEAP. The EP models developed specifically for EP in developing countries are mainly goal programming or linear programming models that do not align with the requirements for the current work. These models were also developed for geographic levels below the national level. An energy model specific to woodfuel would not include additional FE carriers and would therefore have to be used in parallel to additional EP models and would require detailed data GIS data, which was not in the scope of the current work.

The review did not identify a specific model that fulfilled the described characteristics. A decision was made, therefore, to construct a model within the flexible MATLAB programming environment, allowing for user defined inputs and outputs as well as energy demand and supply side modeling methodologies. Construction of this model together with the development of a national EP case study also allowed for a model that was specific to the energy system of application but also sufficiently generic to apply to other energy systems with some modification.

4.3 Energy accounting

The central outputs from the national energy systems model are the data required for measuring the quantifiable attributes for evaluation of alternatives; however, the model also depicts the energy flows through the national energy system. This information, both inputs and outputs, from the energy modeling activity is essential for any decision making activity connected to EP. Detailed and reliable data allows DMs to make informed decisions, however it must be presented in an accessible format (Bhattacharyya, 2011).

Both the energy model constructed and the data extracted are specific to the purpose of the EP activity, however Bhattacharyya (2011) discussed five common information requirements.

1. Energy use by various economic activities.
2. Energy resources, transformation and delivery to various users.
3. Technical and operational statistics of the plants and installations.
4. Financial and cost information.
5. Macro-economic and other social information.

To address these information requirements, the national energy modeling activity would require an energy accounting system. The current work adopted an energy accounting system that allowed for evaluation of PE imports and indigenous resources, transformation activities and the energy flows to the various energy demand sectors. The demand within each sector was disaggregated into the various FE services and FE carriers.

One commonly used tool for accounting in this regard is the national energy balance (NEB). The NEB shows all the energy flows, typically for a given year, through the national energy system. The NEB is typically disaggregated into the various PE resources and FE carriers of concern. The accounting of this energy, in a common energy unit (e.g. ktoe, GJ, MMBtu, etc.), is shown from the PE inputs, through transformation to the FE demand sectors (Bhattacharyya, 2011).

An additional tool of aid in accounting for and presenting energy flows are Sankey diagrams. While the energy balance is a tabulated presentation of data, the Sankey diagram provides a graphical “map” showing the path that energy follows from its primary forms through to the demand sectors, services or end uses depending on the level of disaggregation required.

	PE resources ------ FE carriers
Production (+) Imports (+) Exports (-) Bunkers (-) Stock changes (+ or -) PE requirements (total)	PE supply
Statistical difference Transformation input (-) Energy sector own use (-) Transmission and distribution losses (-) Net FE supply available	Transformation
Net domestic consumption FE consumption Residential consumption Service consumption Industry consumption Transport consumption Agriculture Consumption Non-energy uses	FE demand

Figure 4-3 – Main flows in energy accounting balance (Bhattacharyya, 2011; IEA, 2012a)

Sankey diagrams have become a common and effective graphic tool to map the scale of energy use through energy systems (Cullen and Allwood, 2010; Schmidt, 2008; IEA, 2015a). An example of a Sankey diagram for a simplified generic national energy system is depicted in Figure 4-4.

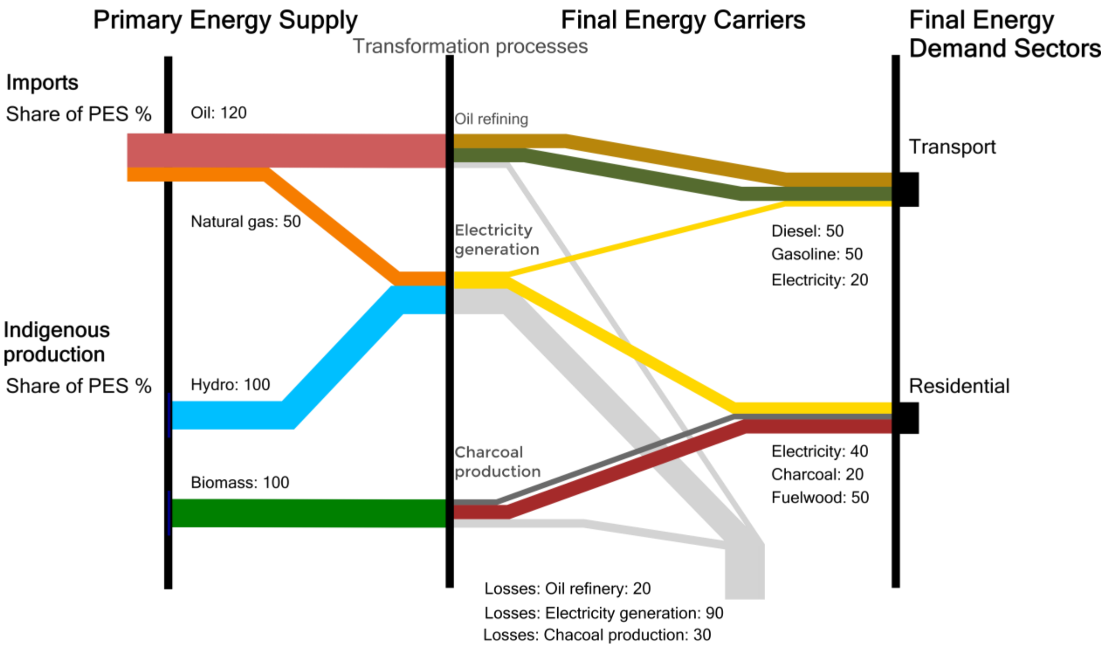

Figure 4-4 - Sankey diagram of a simplified generic national energy system [ktoe]

Modeling of the national energy systems requires multiple distinct energy flows. The flow of energy through the system, in a Sankey diagram, is depicted with lines, or streams, where thickness represents the scale of energy flow and color differentiates between the various PE resources and FE carriers considered. The accounting of national energy systems requires the separation of PE, FE and possibly useful energy depending on the necessities of the accounting activity (useful energy is not depicted in Figure 4-4). A clear distinction between these energy categories and the various PE resources and FE carriers is required in the Sankey diagram (Giampietro and Sorman, 2012).

The Sankey diagram allows for this separation through the different areas from left to right of the diagram. Energy transformation stages (e.g. electricity generation, charcoal production and oil refining) can be depicted as nodes where the change in energy category (PE to FE) occurs accounting for input, outputs, and losses. Where conversion technologies are not expressed as nodes the diagram can be arranged with vertical lines dividing the energy categories as done in previous works by Cullen and Allwood (2010) and Ma et al. (2012).

4.3.1 Additional accounting considerations

There is no single definite method for accounting for the PE requirement for non-combustible energy sources such as renewable energy sources in transformation processes (e.g. electricity and heat generation) (Edenhofer et al., 2011).

Five plausible methodologies exist for accounting of the PE requirements from non-combustible energy sources in electricity, heat and cogeneration transformation processes. All of these methodologies account for electricity generation from combustible sources, including fossil fuels, biomass and waste, in a common fashion based on calorific value of the fuel, technology efficiency, and the fuel required for generation of a unit of electricity or heat. The methodologies differ in how they account for the transformation of non-combustible PE (Edenhofer et al., 2011; Stoffregen and Schuller, 2014). Table 4-2 presents the differences between these accounting methodologies.

From an analysis of the energy balance of Ghana presented by the EC (2013a) it is apparent that the direct equivalent method (method 2 of Table 4-2) was used in accounting for PE in non-combustible renewable electricity generation.

The calculation of attributes for both objectives 1 *Maximize PE security* and *6 Minimize the influence of the energy system on the global climate* (Section 3.6) were compatible with this method. The calculation of the attribute for objective 6 followed the guidelines from the UN and IPCC for GHG emissions accounting, both of which adhere to the direct equivalent method.

For the current work, the direct equivalent method would suffice for considerations within the energy model as well as those pertaining to the evaluation of energy alternatives through the quantifiable attributes.

Table 4-2 – Methods to calculate PE equivalents and conversion efficiencies

Accounting option[1]	Methodology	Adopted by:
1. Zero equivalent	No PE is accounted for transformation of non-combustible resources. *PE required for renewable non-combustible FE generation is effectively accounted for as equal to zero.*	Rarely used. Plausible when PE is supplied by recovered residues such as gas from sewage of landfills.
2. Direct equivalent	A direct equivalence between the FE generated and the PE resource is used. The remaining PE is considered to remain in the environment. *For non-combustible renewables this means that 1 unit of FE requires 1 unit equivalent of PE.*	UN & reports to the IPCC
3. Physical energy content	PE is considered the first energy form downstream in the production process for which multiple energy uses are practical. *For hydro and PV electricity is the first practical use and so 100% conversion efficiency is assumed.* *For geothermal, nuclear and solar thermal the heat is the first usable form. Conversion efficiencies then are used to account for transformation into other FE carriers.*	IEA & Eurostat
4. Substitution	PE is considered the form that it is first accounted for in a statistical balance prior to transformation to other forms of energy, e.g. FE. *In theory this requires calculation of the kinetic energy necessary to produce a unit of electricity from a wind turbine, for example.* *To avoid this complication, the conversion efficiencies of the hypothetical fossil fuel plants which were substituted by non-combustible renewable energy generation to produce the FE, e.g. electricity, are used.*	US EIA & BP
5. Technical conversion efficiencies	PE is defined as the energy content of carriers that has not undergone any conversion. *Here technical conversion efficiencies are required to evaluate the PE in an energy sources and the generated FE. Here hydro, for example, requires the ratio of electricity generated to the potential energy of water which is defined by the height and amount of water used within a time period. Additional technical conversion efficiencies have also been defined for other renewable sources* (Stoffregen and Schuller, 2014).	Association of German Engineers (VDI) – Standard 4600: Cumulative energy demand (KEA)

1. Multiple variations on the names used here exist and there is no standard terminology.
A discussion and comparison of these methods can be found in Stoffregen and Schuller (2014)
References: (Edenhofer et al., 2011; Giampietro and Sorman, 2012; Stoffregen and Schuller, 2014)

4.4 Overview of the national energy systems model

The national energy system model used in this work, as characterized in the proceeding Sections 4.1 to 4.3, consisted of two central modules. The first was the energy demand module, which was used to calculate the FE demand for the energy demand sectors of the economy for all FE carriers considered. The second module was used to evaluate the PE supply and transformation requirements necessary for the energy supply and demand balance.

The inputs to the national energy systems model consisted of the key parameters which are described in more detail in the Chapter 5, detailing the case study. Inputs also consisted of technical considerations and constraints for the system which are described in the sections which follow. Energy access was of note here as it as considered both a preliminary input to the model and a quantifiable attribute considered in the evaluation of alternatives.

The final outputs of from these two modules were fed to the quantifiable attributes used within the MCDA model (Chapter 3 and Chapter 5). A diagram of the national energy system model developed for the current work is presented in Figure 4-5.

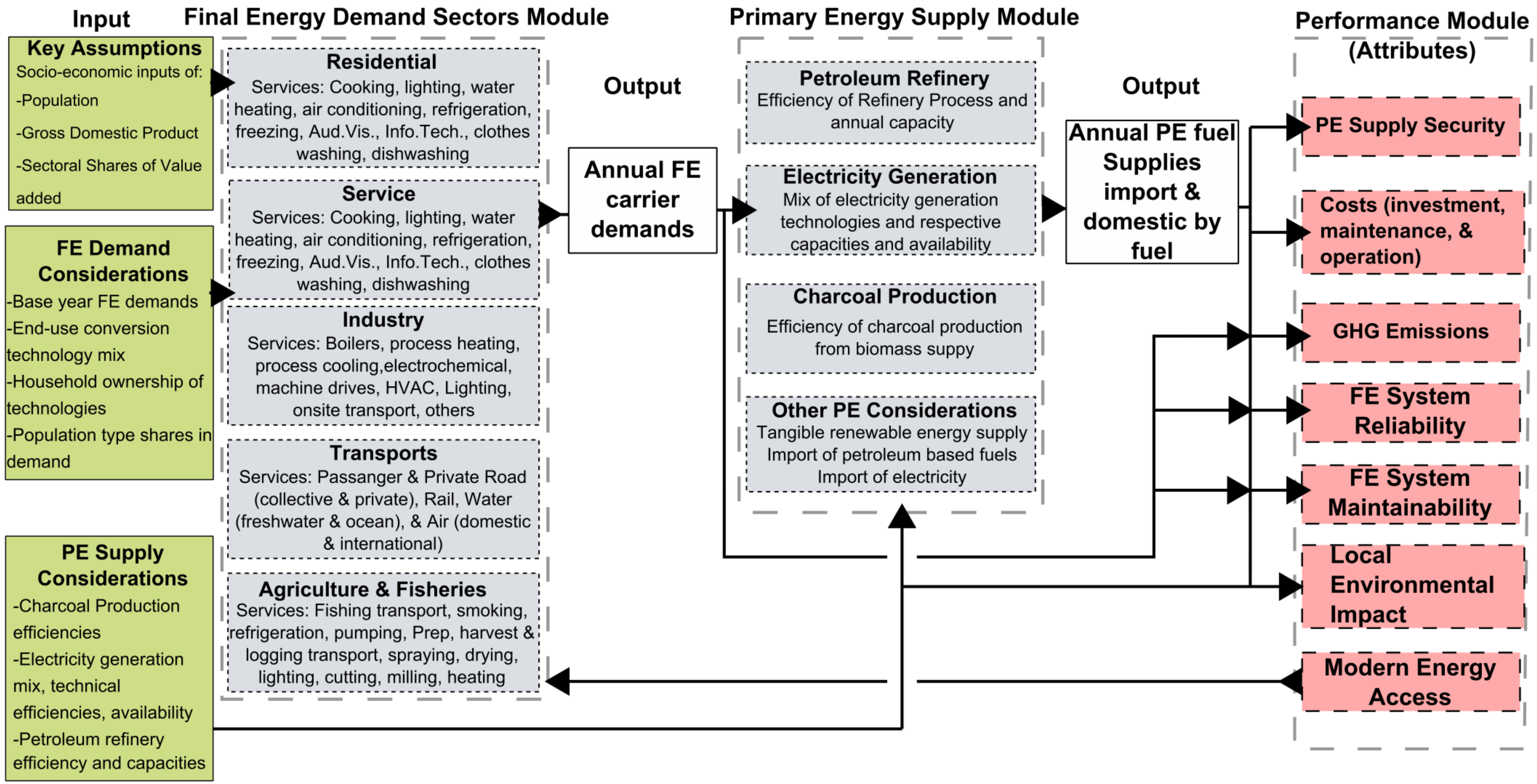

Figure 4-5 - National energy systems model diagram

4.5 Disaggregation of energy data and modeling methodology

The energy data representing national level accounts are typically found in an aggregated form in NEBs or Sankey Diagrams. These aggregated data sets, for example total FE demand for electricity, represent data for different segments of the energy system (e.g. electricity demand for each FE demand sector and all FE end-uses demand which represent uses of electricity).

In the modeling of the national energy system this aggregated data is typically available for a base year, y=0, although not always. In order to represent the different energy demand sectors in the model, data for each sector, carrier and use is required, and so this requires disaggregation of the national level data to the requirements of the aggregation level chosen for the model, see Section 4.2.2 (e.g. FE demand for fuelwood for cooking in the Residential sector). This disaggregated data is then used as an input for the base year, y=0, in the FE demand model. With this base year data and the assumptions made for the EP activity, the energy demand is projected for the planning horizon until year N, y=N, in disaggregated form. The disaggregated data for the projection can then be combined to an aggregate value, (e.g. total FE demand for fuelwood). These aggregated values are then used as the national level data for the NEB (e.g. total fuelwood demand in y=N or demand at the sector level). These aggregate values are used to calculate the PE requirements necessary to meet FE demand (e.g. biomass requirements to meet fuelwood and charcoal production demand). This disaggregation-aggregation cycle, as used in in the modeling methodology of this work, is depicted in Figure 4-6.

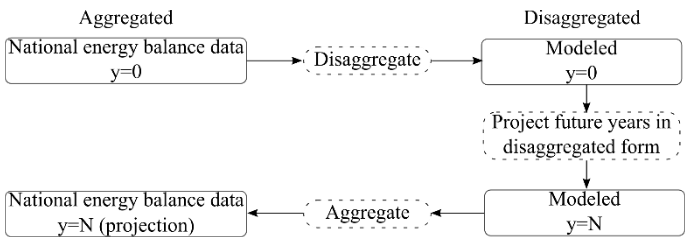

Figure 4-6 - Disaggregation-aggregation cycle of energy modeling methodology

4.6 Energy demand considerations

The current section presents the modeling methodology within the energy demand module. The energy demand considerations and equations are presented to as much of a degree as permissible, given the application of the model.

To this end it must be stated that the energy model, both the FE demand and PE resources and transformation considerations were constructed for eventual application to the case study country of Ghana, which is presented in more detail in Chapter 5. For this reason, specific considerations were necessary, in the modeling methodology, in order to ensure that the model was appropriate for this application. For example, the FE demand disaggregation methodology must be suitable to the level of aggregation of national data available, and the FE sectors and subsectors in the model must reflect the reality of the actual energy system being considered.

For this reason, the energy demand and supply model presented is not completely generic (e.g. readily applicable to any national energy system), but a generic energy model built for the case considered. It can still be applied to other countries, but some minor modifications may be required.

In an attempt to concretize the FE demand considerations, examples are provided for Ghana, the case study country. These values represent base year, y=0, data, which are established with the modeling considerations made in this chapter, and are used as the input to the specific application of the model which is presented in detail in Chapter 5.

4.6.1 Sectoral analysis

The FE demand for the respective FE carriers are first determined at the level of the FE service within each of the FE demand sectors. The total FE demand for each year is determined by the sum of the FE demand for the FE carriers considered from each of the FE demand sectors, Eq. 4-2.

The total FE demand for the base year 2008 was determined from data available in the most recent national EP activity the Strategic National Energy Plan (SNEP) conducted for the case study country (EC, 2006a). Where values were not explicitly stated, assumptions were made to calculate values that were in agreement with the information available. The FE demand requirements for the country in the year 2008 are shown in Table 4-3.

$$Q_{i,y}^{total} = \sum_{k=1}^{S} Q_{k,i,y} \quad [ktoe] \qquad \textbf{Eq. 4-2}$$

Where:

$Q_{i,y}^{total}$: Total FE demand for FE carrier *i* in year *y* [ktoe]

$Q_{k,i,y}$: FE demand from sector *k=1, 2, 3, …, S* for FE carrier *i* in year y [ktoe]

Table 4-3 - FE carrier demand disaggregated by sector: Ghana 2008

[ktoe]	Fuelwood	Charcoal	Kerosene - general	LPG	Electricity	Diesel	Gasoline	Gasoline - premix	Solar thermal, direct	RFO[1]	Kerosene -aviation
Total FE Consumption	**5,824.50**	**1,441.00**	**81.37**	**243.00**	**987.36**	**1,224.00**	**745.36**	**111.30**	**22.76**	**191.58**	**146.78**
Residential	4,234.49	1,409.80	81.37	83.16	602						
Service	117.48	31.20		32.40	129.00						
Industry	1,456.12				252.94	110.16				191.58	
Transport				127.44		1,040.40	745.36				146.78
Agriculture & Fishery	16.41				3.42	73.44		111.30	22.76		

1. Refined fuel oil

(Armah, 2003; EC, 2014, 2006a) and calculations

4.6.2 Residential sector

FE demand in the Residential sector consists of the energy required by the population to provide FE services at the household level. The Residential sector as a whole represents 24% of global FE consumption, a substantial share (IEA, 2012a).

The demand for FE services within the sector can vary for different populations depending on a number of factors which include income, customs and habits, and climatic conditions. Countries, for example, that experience sufficiently low temperatures to require space heating in residential housing, have a different set of FE service demand than countries that are located in warm climates in which heating demand is not represented.

The FE services and the FE carriers considered for the Residential sector model are those that are representative of the Residential sector of Ghana. Services such as space heating and clothes drying are absent, or negligible, in the FE demand, due to the climate and customs. The FE carriers and the FE services considered within the Residential sector model of Ghana are presented in Table 4-4.

The Residential sector model consists of the three subsectors for the population types (1) CoreUrban, (2) PeriUrban and (3) Rural populations.

To establish FE demand in the base year the total Residential sector FE demand for each of the FE carriers was required. Data for the FE carriers essentially ends at the level of gross FE demand, and little information is available beyond this level regarding the shares of FE demand for each FE carrier that is used to meet demand for each of the FE services at the household level. While data for the FE demand for the various FE carriers was available, there was no data available for the shares of FE carrier demand that each FE service represented.

The breakdown of the FE carrier demand into the respective shares that went to meet each FE service was based both on data and best assumptions. These data and assumptions were based on information discernable from the EC (2006a) and verified with EP actors in Ghana (EC, 2014). The share that each FE service represents in FE carrier demand for the base year is presented in Table 4-4.

Residential FE demand excludes informal Commercial and Industrial sector activities, such as cooking, which in many developing countries is done within the household and then taken to be sold at an external location (EC, 2006a). These informal activities conducted at the household level are considered commercial activities as the FE service produces products are sold outside of the household. The difference here is subtle as a share of the cooking could go to household consumption and a share to commercial consumption.

The FE demand attributable to the specific services is calculated by the product of the total FE demand for each carrier and share that each service represents in FE carrier demand as shown in Eq. 4-3.

$$Q_{i,s,y=0}^{Res} = Q_{i,y=0}^{Res} \times Share_{s,i,y=0} \ [ktoe] \qquad \textbf{Eq. 4-3}$$

Where:

$Q_{i,s,y=0}^{Res}$: FE demand for FE carrier *i* attributable to FE service *s*, in year *y=0* [ktoe]

$Q_{i,y=0}^{Res}$: Aggregate FE demand for FE carrier *i* in year *y=0* [ktoe]

$Share_{s,i,y=0}$: Share that FE service s represents of FE demand for carrier i, and year *y=0* [%]

The composite FE carrier demand separated by FE services calculated in Eq. 4-3 represents demand of the entire Residential sector. To disaggregate this composite demand into the demand attributable to each of the subsector population types additional calculations were required.

Table 4-4 - Residential: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE Services	Share that FE service represents of FE carrier demand [%]				
	Fuelwood	Charcoal	Kerosene	LPG	Electricity
Lighting			100		25
Cooking	75	75		75	
Water heating	25	25		25	5
Refrigeration					20
Freezing					10
Air conditioning					5
Clothes washing					5
Dishwashing					5
Audiovisual					20
Information technology					5

(EC, 2014, 2006a) and assumptions

A system of equations was established to solve for the FE demand for each carrier and service combination attributable to the three population types, $Q_{p,i,s,y=0}$, where *p* is the index for population type, and finally the share that each population type represents in the total FE demand for each FE carrier and service combination. Three equations were required for the three unknowns of demand for CoreUrban, PeriUrban and Rural populations for each FE carrier and service combination.

The first equation results from the fact that FE carrier demand is also equal to the total for all population types of the product of the FE intensity (FEI) [ktoe/household] and the number of households, Eq. 4-4.

$$Q_{i,s,y=0}^{Res} = \sum_{p=1}^{3} FEI_{p,i,s,y=0} \times A_{p,i,y=0} \times HHS_{p,y=0} \quad [ktoe]$$ **Eq. 4-4**

Where:

$FEI_{p,i,s,y=0}$: FEI for population type *p* for FE carrier *i* and FE service *s*, in year *y=0* [ktoe/household]

$A_{p,i,y=0}$= Share of HHS of population type *p* that has access to carrier *i* in year *y=0* [%]

$HHS_{p,y=0}$: Households of population type *p*, in year *y=0* [household]

The second two equations result from the ratios of FE demand attributable to the CoreUrban population and the remaining PeriUrban and Rural populations as shown in Eq. 4-5 and Eq. 4-6 respectively. Assumptions were required for each of the ratios $\beta_{i,s,y=0}^{CU/PU}$ and$\beta_{i,s,y=0}^{CU/R}$. These ratios were assumed based on best judgement from information in EC (2006a) and are shown in

Table 4-5. (Electricity provided by minigrid and standalone systems are not represented in this table as they were assumed to be insignificant in the base year)

$$\beta_{i,s,y=0}^{CU/PU} = \frac{FEI_{p=1,i,s,y=0} \times A_{p=1,i,y} \times HHS_{p=1,y=0}}{FEI_{p=2,i,s,y=0} \times A_{p=2,i,y} \times HHS_{p=2,y=0}} \quad [-] \qquad \textbf{Eq. 4-5}$$

Eq. 4-5 can be rewritten as:

$$FEI_{p=1,i,s,y=0} \times A_{p=1,i,y} \times HHS_{p=1,y=0} - \beta_{i,s,y=0}^{CU/PU}\left(FEI_{p=2,i,s,y=0} \times A_{p=2,i,y} \times HHS_{p=2,y=0}\right) - 0 = 0$$

Where:

$\beta_{i,s,y=0}^{CU/PU}$: Ratio of FE demand for carrier i, and service s, attributable to Core Urban and PeriUrban populations in year y=0 [-]

$$\beta_{i,s,y=0}^{CU/R} = \frac{FEI_{p=1,i,s,y=0} \times A_{p=1,i,y} \times HHS_{p=1,y=0}}{FEI_{p=3,i,s,y=0} \times A_{p=3,i,y} \times HHS_{p=3,y=0}} \quad [-] \qquad \textbf{Eq. 4-6}$$

Eq. 4-6 can be rewritten as:

$$FEI_{p=1,i,s,y=0} \times A_{p=1,i,y} \times HHS_{p=1,y=0} + 0 - \beta_{i,s,y=0}^{CU/R}(FEI_{p=3,i,s,y=0} \times A_{p=3,i,y} \times HHS_{p=3,y=0}) = 0$$

Where:

$\beta_{i,s,y=0}^{CU/R}$: Ratio of FE demand for carrier i, and service s, attributable to Core Urban and Rural populations in year y [-]

This system of equations was solved for $FEI_{p,i,s,y=0}$ respective to each subsector, representing the population types. These FE intensities were then used to solve for the FE demand $Q_{p,i,s,y=0}$ for each FE carrier and service combination attributable to each population type with Eq. 4-7. The total FE demand for each FE service is presented in Table 4-6.

$$Q_{p,i,s,y=0}^{Res} = FEI_{p,i,s,y=0} \times A_{p,i,y=0} \times HHS_{p,y=0} \quad [ktoe] \qquad \textbf{Eq. 4-7}$$

Where:

$Q_{p,i,s,y=0}^{Res}$: FE demand from population type *p* for FE carrier i attributable to FE service s, in year *y=0* [ktoe]

$A_{p,i,y=0}$= Share of HHS of population type *p* that has access to carrier *i* in year *y=0* [%]

$HHS_{p,y=0}$: Households of population type *p*, in year *y=0* [household]

Table 4-5 - Residential: The CoreUrban/Peri/Urban and CoreUrban/Rural ratios of subsector FE demand for service & carrier combinations: Ghana 2008

FE service – carrier combination	$\beta_{i,s,y=0}^{CU/PU}$	$\beta_{i,s,y=0}^{CU/R}$
Cooking – Biomass	1/2	1/3
Cooking – Charcoal	1/2	1/3
Cooking – LPG	5	5
Cooking – Electricity- Grid	0	0
Lighting – Kerosene	1/5	1/20
Lighting – Electricity- Grid	2	6
Water heating – Biomass	1/2	1/3
Water heating – Charcoal	1/2	1/3
Water heating – LPG	5	5
Water heating – Electricity- Grid	2	2
Refrigeration – Electricity- Grid	2	5
Freezing – Electricity	2	5
Audiovisual – Electricity	2	4
Information Technology – Electricity- Grid	3	10
Air conditioning – Electricity- Grid	3	10
Clothes washing – Electricity- Grid	3	10
Dish washing – Electricity- Grid	3	10

(EC, 2006a)

The FE intensity expressed in Eq. 4-4 can alternatively be expressed as the energy demand per unit of household conversion technology [ktoe/appliance] as shown in Eq. 4-8. Expressing the FEI in these units allows for future projection of FE demand which includes changing ownership levels of appliances (energy conversion technologies) in residential households as well as changes in the efficiency of these appliances.

$$FEI_{p,i,s,y=0}^{Res,\ app} = \frac{Q_{p,i,s,y=0}^{Res}}{A_{p,i,y=0} \times HHS_{p,y=0} \times Own_{p,i,s,y=0}} \quad [ktoe/appliance] \qquad \textbf{Eq. 4-8}$$

Where:

$FEI_{p,i,s,y=0}^{Res,\ app}$: The FE intensity per unit of appliance (e.g. appliance or technology) for population type *p* for FE carrier *i* attributable to FE service *s*, in year *y* [ktoe/appliance]

$Own_{p,i,s,y=0}$: Level of ownership of units at the household level for population type y for FE carrier i attributable to FE service *s*, in year *y* [appliance/household]

$A_{p,i,y=0}$= Share of HHS of population type *p* that has access to carrier *i* in year *y=0* [%]

$HHS_{p,y=0}$: Households of population type *p*, in year *y=0* [household]

The calculated FE demand for each of the FE service-carrier combinations is shown in Table 4-6 for each of the subsector population types for the year 2008. The corresponding FE intensities for the base year are shown in Table 4-7.

Table 4-6 - Residential: FE demand for each service & carrier combination by subsector: Ghana 2008

	FE Demand [ktoe]			
FE service – carrier combination	CoreUrban	PeriUrban	Rural	Total
Cooking – Biomass	332.48	414.52	2,428.86	3,175.86
Cooking – Charcoal	156.88	60.96	839.51	1,057.35
Cooking – LPG	53.59	7.06	1.72	62.37
Cooking – Electricity- Grid	-	-	-	-
Lighting – Kerosene	6.86	7.70	66.81	81.37
Lighting – Electricity- Grid	95.84	29.87	24.79	150.50
Water heating – Biomass	110.83	138.17	809.62	1,058.62
Water heating – Charcoal	52.29	20.32	279.84	352.45
Water heating – LPG	18.76	1.36	0.67	20.79
Water heating – Electricity- Grid	14.42	4.49	11.19	30.10
Refrigeration – Electricity- Grid	74.23	23.14	23.04	120.40
Freezing – Electricity	37.11	11.57	11.52	60.20
Audiovisual – Electricity	70.84	22.08	27.48	120.40
Info. Tech. – Electricity- Grid	22.08	4.59	3.43	30.10
Air conditioning – Electricity- Grid	22.08	4.59	3.43	30.10
Clothes washing – Electricity- Grid	22.08	4.59	3.43	30.10
Dish washing – Electricity- Grid	22.08	4.59	3.43	30.10

calculations

Table 4-7 - Residential: FE Intensity by FE service & carrier combination by subsector: Ghana 2008

	FE Intensity at the appliance level [ktoe/appliance]		
FE service – carrier combination	CoreUrban	PeriUrban	Rural
Cooking – Biomass	1.32E-03	6.36E-04	9.54E-04
Cooking – Charcoal	2.74E-04	6.96E-04	2.58E-03
Cooking – LPG	5.70E-04	2.95E-03	1.45E-03
Cooking – Electricity- Grid	-	-	-
Lighting – Kerosene	2.90E-05	2.16E-05	3.37E-05
Lighting – Electricity- Grid	1.11E-04	9.26E-05	8.35E-05
Water heating – Biomass	4.40E-04	2.12E-04	3.18E-04
Water heating – Charcoal	9.13E-05	2.32E-04	8.61E-04
Water heating – LPG	1.99E-04	5.69E-04	5.69E-04
Water heating – Electricity- Grid	3.57E-04	6.31E-04	6.31E-04
Refrigeration – Electricity- Grid	1.42E-04	1.07E-04	1.94E-04
Freezing – Electricity	2.55E-04	2.46E-04	3.49E-04
Audiovisual – Electricity	9.14E-05	6.96E-05	1.05E-04
Info. Tech. – Electricity- Grid	3.15E-04	2.47E-04	3.46E-04
Air conditioning – Electricity- Grid	1.15E-03	6.92E-03	2.08E-03
Clothes washing – Electricity- Grid	1.09E-03	3.46E-03	2.08E-03
Dish washing – Electricity- Grid	1.09E-03	3.46E-03	2.08E-03

calculations

4.6.3 Service sector

The Service sector consists of the buildings and activities involved in providing both commercial and public services to the population. Globally the sector represents a share of FE consumption of 8%, which is less significant than sectors such as Residential and Transport and Industry (IEA, 2012a). The Service sector is commonly less energy intensive than the

Industry sector for example. However, the GVA of the sector is often seen to grow taking shares from Industry, in the total GVA, as countries develop.

The activities included in the Service sector are vast and the sector has frequently been defined as consisting of everything that is not contained in the remaining sectors (MacDonald, 2004). The FE demand from the Service sector includes a diverse group of buildings and activities such as commercial retail stores, offices, restaurants, and hotels. It also encircles public services such as schools, hospitals and health centers, government offices and defense installations.

The Service sector, in the current work, is not disaggregated into subsectors, but alternatively treated as a whole and represented by various FE demands for services. In the absence of a detailed breakdown of the FE services that the demand from the sector comprises, the FE services considered in the current model for the Service sector are assumed to be identical to those in the Residential sector.

The FE carrier demand for each FE service was disaggregated into shares of the total demand established by both data and best assumptions. These were based on the national energy plan from the case study country and verified with EP actors in Ghana (EC, 2014, 2006d). The share that each FE service represents of total FE carrier demand for the base year is presented in Table 4-8.

The FE demand attributable to the FE services is calculated by the product of the total FE demand for each carrier and the share that each service represents in FE carrier demand as shown in Eq. 4-9.

$$Q_{i,s,y=0}^{Ser} = Q_{i,y=0}^{Ser} \times Share_{s,i,y=0} \ [ktoe] \qquad \textbf{Eq. 4-9}$$

Where:

$Q_{i,s,y=0}^{Ser}$: FE demand for FE carrier *i* attributable to FE service *s*, in year *y=0* [ktoe]

$Q_{i,y=0}^{Ser}$: Aggregate FE demand for FE carrier *i* in year *y=0* [ktoe]

$Share_{s,i,y=0}$: Share that FE service *s* represents of FE demand for carrier *i* and year *y=0* [%]

Table 4-8 – Service: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE Services	Share that FE service represents of FE carrier demand [%]			
	Fuelwood	Charcoal	LPG	Electricity
Lighting				54
Cooking	85	85	88	
Water heating	15	15	12	3
Refrigeration				10
Freezing				10
Air conditioning				10
Clothes washing				1
Dishwashing				1
Audiovisual				3
Information technology				8

(EC, 2014, 2006a) and assumptions

The FEI for the Service sector is represented by the energy use per unit of GVA by the sector [ktoe/GVA^{Ser}] for each of the FE service-carrier combinations as in Eq. 4-10. The FEI allows for projection of FE demand considering shifts in the mix of conversion technologies used in the Service sector and their respective energy efficiencies.

$$FEI_{i,s,y=0}^{Ser} = \frac{Q_{i,s,y=0}^{Ser}}{\omega_{i,s} \times GVA_{y=0}^{Ser}} \quad [ktoe/monetary\ units]$$ **Eq. 4-10**

Where:

$FEI_{i,s,y=0}^{Ser}$: FEI at the energy service level for carrier *i* and service *s*, in year *y=0* [ktoe/US $]

$GVA_{y=0}^{Ser}$: GVA by the Service sector in the year *y=0* [$monetary\ units$]

$\omega_{i,s}$: Contribution to GVA of carrier *i* in the service *s*. [%]

The share that energy consumption contributes to the total GVA of the sector was assumed to be 100%.

The resulting FE demand for each FE service-carrier combination in the Service sector as well as the corresponding FE intensity for the year 2008 is shown in Table 4-9.

Table 4-9 – Service: FE demand for each FE service – carrier combination: Ghana 2008

FE service – carrier combination	FE Demand [ktoe]	FE Intensity [ktoe/US $]
Cooking – Biomass	99.86	9.08E-05
Cooking – Charcoal	26.52	3.39E-05
Cooking – LPG	28.51	5.51E-05
Cooking – Electricity- Grid	-	-
Lighting – Kerosene	-	-
Lighting – Electricity- Grid	69.66	1.31E-04
Water heating – Biomass	17.62	1.99E-05
Water heating – Charcoal	4.68	5.98E-06
Water heating – LPG	3.89	7.26E-06
Water heating – Electricity- Grid	3.87	7.27E-06
Refrigeration – Electricity- Grid	12.90	2.41E-05
Freezing – Electricity	12.90	2.41E-05
Audiovisual – Electricity	3.87	7.16E-06
Info. Tech. – Electricity- Grid	10.32	2.08E-05
Air conditioning – Electricity- Grid	12.90	2.60E-05
Clothes washing – Electricity- Grid	1.29	2.60E-06
Dish washing – Electricity- Grid	1.29	2.60E-06

calculations

4.6.4 Industry sector

The Industry sector represents a significant share of both PE and FE demand in many countries worldwide. FE consumption of the sector represents 37% of the global consumption (IEA, 2012a). Industry subsectors that represent the most significant energy intensities include iron and steel, cement, chemical and petrochemical, pulp and paper as well as aluminum (IEA, 2010d).

Following the national energy plan from EC (2006d), the Industry sector in Ghana consists of 5 subsectors, namely: formal manufacturing, Volta Aluminum Company (VALCO) – Aluminum mining, construction, utilities, and informal activities.

The Industry sector differs from other sectors as the representative FE services in the sector do not vary depending on the climate, location, consumer behaviors or income levels. For this reason, industrial sector processes are similar throughout the world, making comparisons between countries possible both in terms of the EI of processes and the standard FE services that are employed in the sector. Previous work has capitalized on this universality in the industrial sector and used a standard set of nine FE services to represent demand in the sector (DOE, 2012; Haydt, 2012). These FE services consist of (1) conventional boilers (2) process heating (3) process cooling and refrigeration (4) electrochemical (5) machine drive (6) facility HVAC (7) facility lighting (8) onsite transport and (9) other services.

The breakdown of the FE carrier demand into the respective shares that went to meet each FE demand of the Industry subsectors was based both on data and best assumptions. The information discernable from the EC (2006a) was used to support this effort. These assumptions were verified with EP actors in Ghana (EC, 2014). The total FE demand was disaggregated into the shares attributable to each demand subsector for the base year as shown in Table 4-10.

Table 4-10 – Industry: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

Subsectors	Share that subsector represents of FE carrier demand [%]			
	Fuelwood	Electricity	Diesel	RFO*
Manufacturing		14	40	90
Aluminum-VALCO		55	5	10
Mining		23	50	
Construction		3	3	
Utilities		5	2	
Informal activities	100			

(Armah, 2003; EC, 2014, 2006a) and assumptions
* Refined Fuel Oil (RFO)

The standard set of FE services was used to further disaggregate the FE demand attributable to each subsector to the share that each FE service represents of the demand. The shares of FE demand for each FE service were determined from data or best assumptions from the EC (2006a).

The formal manufacturing subsector, Table 4-11, consists of activities including production of iron and steel, cement, and other manufacturing activities excluding aluminum production.

The aluminum manufacturing activities, Table 4-12, are broken out into a separate subsector due to the significant energy demand of VALCO the aluminum manufacturing company. VALCO is the single largest, non-utility, FE demand on the national electricity grid when in operation and represented 13-17% of the total FE demand of the Industry sector until 2003 and 50-60% of electricity demand.

Table 4-11 – Manufacturing: Estimated shares of FE carrier demand disaggregated by service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Manufacturing	Fuelwood	Electricity	Diesel	RFO
Conventional boilers		2.55	25.63	25.63
Process heating		11.47	61.77	61.77
Process cooling & refrigeration		6.83	0.45	0.45
Electrochemical		7.73		
Machine drive		52.37	3.11	3.11
Facility HVAC		8.63	5.15	
Facility lighting		6.50		
Onsite transport		0.24	0.76	0.76
Other		3.68	3.14	3.14

(Armah, 2003; EC, 2014, 2006a) and assumptions

Table 4-12 – Aluminum: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Aluminum-VALCO	Fuelwood	Electricity	Diesel	RFO
Conventional boilers			3.85	3.85
Process heating		4.58	86.54	86.54
Process cooling & refrigeration		0.65	1.92	1.92
Electrochemical		78.43		
Machine drive		12.42	0.96	0.96
Facility HVAC		1.31	3.85	3.85
Facility lighting		1.96		
Onsite transport			0.96	0.96
Other		0.65	1.92	1.92

(Armah, 2003; EC, 2014, 2006a) and assumptions

The mining subsector, Table 4-13, includes underground and surface mining as well as quarrying. The construction subsector, Table 4-14, includes all construction activities in the country.

Table 4-13 – Mining: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Mining	Fuelwood	Electricity	Diesel	RFO
Conventional boilers				
Process heating				
Process cooling & refrigeration				
Electrochemical				
Machine drive		77.80	95.06	
Facility HVAC		16.98		
Facility lighting		5.22		
Onsite transport			4.94	
Other				

(Armah, 2003; EC, 2014, 2006a) and assumptions

Table 4-14 –Construction: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Construction	Fuelwood	Electricity	Diesel	RFO
Conventional boilers				
Process heating				
Process cooling & refrigeration				
Electrochemical				
Machine drive		90		
Facility HVAC		5		
Facility lighting		5		
Onsite transport				
Other				

(Armah, 2003; EC, 2014, 2006a) and assumptions

The utilities sector, Table 4-15, includes the energy uses in both water provision and electricity generation activities. Electricity generation own-use is not included in this subsector.

Table 4-15 – Utilities: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Utilities	Fuelwood	Electricity	Diesel	RFO
Conventional boilers				
Process heating				
Process cooling & refrigeration				
Electrochemical				
Machine drive		90		
Facility HVAC		5		
Facility lighting		5		
Onsite transport				
Other			100	

(Armah, 2003; EC, 2014, 2006a) and assumptions

The informal industry activities, Table 4-16, were described by EC (2006d) to consist purely of informal food preparation. This subsector represents the only FE demand for fuelwood in the sector and fuelwood is the only FE demand carrier used in the sub-sector.

Table 4-16 – Informal activities: Estimated shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE services	Share that FE service represents of sector FE carrier demand [%]			
Informal activities	Fuelwood	Electricity	Diesel	RFO
Conventional boilers				
Process heating				
Process cooling & refrigeration				
Electrochemical				
Machine drive				
Facility HVAC				
Facility lighting				
Onsite transport				
Other (Cooking)	100			

(Armah, 2003; EC, 2014, 2006a) and assumptions

The FE demand attributable to each of the energy services within the Industry sub-sectors is calculated by the product of (1) the total FE demand for each carrier, (2) the share that each subsector represents in FE carrier demand, and finally (3) the share that the individual FE service represents in FE demand, as shown in Eq. 4-11.

$$Q^{Ind}_{k,i,s,y=0} = Q^{Ind}_{i,y=0} \times Share_{k,i,y=0} \times Share_{k,s,i,y=0} \ [ktoe] \quad \textbf{Eq. 4-11}$$

Where:

$Q^{Ind}_{k,i,s,y=0}$: FE demand for FE carrier *i* attributable to FE service *s* in subsector *k* in year *y=0* [ktoe]

$Q^{Ind}_{i,y=0}$: Total FE demand for FE carrier *i* in year *y=0* [ktoe]

$Share_{k,i,y=0}$: Share that FE demand for carrier *i* represents in subsector *k* in the year *y=0* [%]

$Share_{k,s,i,y=0}$: Share that FE service *s* represents of FE demand for carrier *i* in subsector *k* in the year *y=0* [%]

The FEI for the Industry sector is represented by the energy use per unit of GVA by the sector [ktoe/US $] for each of the FE service-carrier combinations at the subsector level as in Eq. 4-12.

$$FEI^{Ind}_{k,i,s,y=0} = \frac{Q^{Ind}_{k,i,s,y=0}}{\omega_{k,i,s} \times GVA^{Ind}_{y=0}} \quad [ktoe/\text{monetary units}] \quad \textbf{Eq. 4-12}$$

Where:

$FEI^{Ind}_{k,i,s,y=0}$: FEI at the energy service level for carrier *i* service *s* and year y=0 [ktoe/monetary units]

$GVA^{Ind}_{y=0}$: GVA by the Service sector in the year *y=0* [monetary units]

$\omega_{k,i,s}$: Contribution to GVA of the sector for subsector *k*, carrier *i* and service *s* [%]

The share that energy consumption contributes to the total GVA of the sector was assumed to be 100%.

The FE demand for each FE service-carrier combination in the Industry sector is shown in Table 4-17. The corresponding FE intensity is shown in Table 4-18.

Table 4-17 - Industry: FE carrier demand disaggregated by service & carrier combination: Ghana 2008

FE services	FE Demand [ktoe]			
	Fuelwood	Electricity	Diesel	RFO
Manufacturing				
Conventional boilers		0.90	11.29	44.18
Process heating		4.06	27.22	106.50
Process cooling & refrigeration		2.42	0.20	0.77
Electrochemical		2.74		
Machine drive		18.54	1.37	5.36
Facility HVAC		3.06	2.27	8.88
Facility lighting		2.30		
Onsite transport		0.08	0.33	1.31
Other		1.30	1.38	5.41
Aluminum-VALCO				
Conventional boilers			0.21	0.74
Process heating		12.75	4.77	16.58
Process cooling & refrigeration		1.82	0.11	0.37
Electrochemical		218.54		
Machine drive		34.60	0.05	0.18
Facility HVAC		3.64	0.21	0.74
Facility lighting		5.46		
Onsite transport			0.05	0.18
Other		1.82	0.11	0.37
Mining				
Machine drive		44.28	52.36	
Facility HVAC		9.66		
Facility lighting		2.97		
Onsite transport			2.72	
Construction				
Machine drive		7.97		
Facility HVAC		0.44		
Facility lighting		0.44		
Utilities				
Machine drive		11.38		
Facility HVAC		0.63		
Facility lighting		0.63		
Other			5.51	
Informal activities				
Other (cooking)	1,456.13			

(Armah, 2003; EC, 2014, 2006a) and calculations

Table 4-18 - Industry: FE intensity disaggregated by service & carrier combination: Ghana 2008

FE services	FE Intensity [ktoe/US $]			
	Fuelwood	Electricity	Diesel	RFO
Manufacturing				
Conventional boilers		1.56E-12	1.95E-11	7.64E-11
Process heating		7.02E-12	4.70E-11	1.84E-10
Process cooling & refrigeration		4.18E-12	3.41E-13	1.33E-12
Electrochemical		4.73E-12		
Machine drive		3.20E-11	2.37E-12	9.27E-12
Facility HVAC		5.28E-12	3.92E-12	1.54E-11
Facility lighting		3.98E-12		
Onsite transport		1.47E-13	5.78E-13	2.26E-12
Other		2.25E-12	2.39E-12	9.34E-12
Aluminum-VALCO				
Conventional boilers			3.66E-13	1.27E-12
Process heating		1.10E-11	8.24E-12	2.86E-11
Process cooling & refrigeration		1.57E-12	1.83E-13	6.37E-13
Electrochemical		1.89E-10		
Machine drive		2.99E-11	9.15E-14	3.18E-13
Facility HVAC		3.14E-12	3.66E-13	1.27E-12
Facility lighting		4.71E-12		
Onsite transport		9.15E-14	3.18E-13	
Other		1.57E-12	1.83E-13	6.37E-13
Mining				
Machine drive		7.65E-11	9.05E-11	
Facility HVAC		1.67E-11		
Facility lighting		5.13E-12		
Onsite transport			4.70E-12	
Construction				
Machine drive		1.38E-11		
Facility HVAC		7.65E-13		
Facility lighting		7.65E-13		
Utilities				
Machine drive		1.97E-11		
Facility HVAC		1.09E-12		
Facility lighting		1.09E-12		
Other			9.52E-12	
Informal activities				
Other (cooking)	2.52E-09			

(Armah, 2003; EC, 2014, 2006a) and calculations

4.6.5 Transport sector

The Transport sector encompasses the vehicles active in the movement of people and goods within as well as between countries. The Transport sector represented 27% of the FE consumption globally in 2010 (IEA, 2012a).

Transport comprises distinctly different modes of transport and is commonly separated into four different subsectors. These subsectors are Road, Rail, Water, and Air transport modes. The sub-sectors of water and air are further internally divisible into both domestic and international transport (Bhattacharyya, 2011). The current work follows this standard breakdown, Table 4-19, of transport modes as it reflects the breakdown of transport in the case study country (MoT, 2012).

Although the Transport sector is divided into distinct transport mode subsectors, within each of these subsectors the transportation vehicles are employed mainly in the movement of either people or goods and are therefore further divisible into passenger and freight transport. The transport of passengers can be further separated into the two categories of collective passenger transport (e.g. trains) and passenger transport (e.g. private cars) modes (Bhattacharyya, 2011).

The FE carriers that supply the energy for transport consist predominantly of petroleum based products. Alternative FE carriers such as electricity for public and some private transport have entered into the FE mix in the planning activities many developed countries (BITRE and CSIRO, 2008; Fazeli, 2013). In Sub-Saharan African, as in many developing regions, however, the FE mix for transport continues to be dominated by petroleum based fuels (UITP and UATP, 2010; Merven et al., 2012).

The breakdown of the FE carrier demand was based on both data and best assumptions from the most recent national EP activity from the EC (2006a) (Detailed in Part I of the case study in Chapter 5). These assumptions were verified with EP actors in Ghana (EC, 2014). The total FE demand was disaggregated into the shares attributable to each demand subsector for the base year as shown in Table 4-19. For international water transport, subsector FE demand is considered to be zero due to the fact that the subsector consists primarily of international freight vessels which do not seek bunkering services in the country of Ghana (EC, 2006d).

Each of the transport subsectors or modal types comprises different vehicle types which are representative of the collective and private movement of passengers as well as freight. These vehicle types and their respective share in FE demand for the subsector are shown below in Table 4-20 and Table 4-21.

Table 4-19 – Transport: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

Subsectors	Share that subsector represents of FE carrier demand [%]			
	LPG	Diesel	Gasoline	Kerosene-aviation
Road	100	99.3	90	
Rail		0.6		
Water - domestic		0.1	10	
Water - international				
Air – domestic				10
Air – international				90

(EC, 2014, 2006a) and assumptions

Table 4-20 – Transport-Road: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

FE services	Share that subsector represents of FE carrier demand [%]		
Road	LPG	Diesel	Gasoline
Passenger – Private	20	10	80
Passenger – Collective – Minibus[1]		30	6
Passenger – Collective – Large bus		15	3
Passenger – Collective – Taxi	80	5	1
Freight		40	10

(EC, 2014, 2006a) and assumptions

1. Minibus refers to what is locally called a "trotro"

The share in FE demand by carrier for the subsector for each transport type, passenger and freight, for rail transport is shown in Table 4-21.

Table 4-21 – Transport-Rail: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

FE services	Share that subsector represents of FE carrier demand [%]
Rail	Diesel
Passenger	50
Freight	50

(EC, 2014, 2006a) and assumptions

The share in FE demand by carrier for the subsector for each transport type, passenger and freight, for water transport is shown in Table 4-22.

Table 4-22 – Transport-Water domestic: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

FE services	Share that subsector represents of FE carrier demand [%]	
Water -domestic	Diesel	Gasoline
Passenger	50	50
Freight	50	50

(EC, 2014, 2006a) and assumptions

The share in FE by carrier for the subsector for each transport type, passenger and freight, for domestic air transport is shown in Table 4-23.

Table 4-23 – Transport-Air domestic: Estimated shares of FE carrier demand disaggregated by subsector: Ghana 2008

FE services	Share that subsector represents of FE carrier demand [%]
Air - domestic	Kerosene - aviation
Passenger	100
Freight	0

(EC, 2014, 2006a) and assumptions

The share in FE by carrier for the subsector for each transport type, passenger and freight, for international air transport is shown in Table 4-24.

Table 4-24 – Transport-Air-international: Estimated shares of FE carrier demand disaggregated by subsector 2008

FE services	Share that subsector represents of FE carrier demand [%]
Air - international	Kerosene - aviation
Passenger	50
Freight	50

(EC, 2014, 2006a) and assumptions

The FE demand for each of the energy services within the Transport sub-sectors is calculated by the product of (1) the total FE demand for each carrier, (2) the share that each subsector represents in FE carrier demand, and finally (3) the share that the individual FE service represents in FE demand as shown in Eq. 4-13.

$$Q_{k,i,s,y=0}^{Tran} = Q_{i,y=0}^{Tran} \times Share_{k,i,y=0} \times Share_{k,s,i,y=0} \ [ktoe] \qquad \textbf{Eq. 4-13}$$

Where:

$Q^{Tran}_{k,i,s,y=0}$: FE demand for FE carrier i attributable to FE service *s* in subsector *k* in year *y=0* [ktoe]

$Q^{Tran}_{i,y=0}$: Total FE demand for FE carrier *i* in year *y=0* [ktoe]

$Share_{k,i,y=0}$: Share that FE demand for carrier *i* represents in subsector *k*, in year *y=0* [%]

$Share_{k,s,i,y=0}$: Share that FE service s represents of FE demand for carrier *i* in subsector *k*, in year *y=0* [%]

The FEI for the Transport sector is represented by the energy use per unit of activity, Eq. 4-14. The activity in the Transport sector is represented by the mobility, either pkm or tkm, for the sector for each of the FE service-carrier combinations at the subsector level.

$$FEI^{Tran}_{k,i,s,y=0} = \frac{Q^{Tran}_{k,i,s,y=0}}{Mobility_{q,y=0}} \quad [ktoe/pkm \ or \ tkm] \qquad \textbf{Eq. 4-14}$$

Where:

$FEI^{Tran}_{k,i,s,y=0}$: FEI at the energy service level for carrier *i* and service *s*, in year *y=0* [ktoe/pkm or ktoe/tkm]

$Mobility_{s,y=0}$: Mobility in the sector for the year *y=0* for subsector *s*, for passenger [pkm] and freight [tkm]

The FE demand and the FEI for each FE service demand in 2008 are presented in Table 4-25 for the each of the modeled Transport subsectors.

The mobility levels for the specific case of Ghana, the case study country, corresponding to each of the transport subsector types considered are presented in Appendix B.

Table 4-25 – Transport: Estimated Shares of FE carrier demand disaggregated by subsector: Ghana 2008

	FE Demand [ktoe]	FE Intensity [ktoe/pkm or tkm]
Road		
Passenger – Private – LPG	25.49	5.04E-08
Passenger – Private – Diesel	103.31	5.51E-08
Passenger – Private – Gasoline	536.66	4.43E-08
Passenger – Collective – Minibus – Diesel	309.94	5.57E-09
Passenger – Collective – Minibus – Gasoline	40.25	5.12E-09
Passenger – Collective – Large bus – Diesel	154.97	3.94E-09
Passenger – Collective – Large bus – Gasoline	20.12	3.62E-09
Passenger – Collective – Taxi – LPG	101.95	2.82E-08
Passenger – Collective – Taxi – Diesel	51.66	3.08E-08
Passenger – Collective – Taxi – Gasoline	6.71	2.48E-08
Freight – Diesel	154.97	3.94E-09
Freight – Gasoline	20.12	3.62E-09
Rail		
Passenger – Diesel	3.12	2.08E-07
Freight – Diesel	3.12	6.48E-08
Water – domestic		
Passenger – Diesel	0.52	1.82E-10
Passenger – Gasoline	37.27	1.32E-10
Freight – Diesel	0.52	1.34E-09
Freight – Gasoline	37.27	9.69E-10
Water - international	-	-
Air – domestic		
Passenger – Kerosene – aviation	14.68	1.79E-10
Freight – Kerosene – aviation	-	-
Air – international		
Passenger – Kerosene – aviation	66.05	2.58E-08
Freight – Kerosene – aviation	66.05	4.93E-07

(EC, 2014, 2006a) and assumptions

4.6.6 Agriculture and Fishery sector

The Agriculture and Fishery sector comprises the activities of agricultural land preparation, harvest, and post-harvest activities as well as fishing and livestock raising, and the required preservation activities (EC, 2006d). The sector represents the smallest share of total FE consumption worldwide with 2% of FE (IEA, 2012a).

The Agriculture and Fishery sector in the current work is not disaggregated in to subsectors, but alternatively treated as a whole and represented by various FE demands for FE services.

In the absence of a detailed breakdown of the FE services that the demand from the sector comprises, the FE services considered in the current model for the Agriculture and Fishery sector consisted of those detailed in the EP activity for the case study country and best judgement (EC, 2012a).

The FE carrier demand was disaggregated into shares, for each FE service, of the total demand established by both data and best assumptions. These were based on the national energy plan from the case study country and verified with EP actors in Ghana (EC, 2014, 2006d). The share that each FE service represents in FE carrier demand for the base year is presented in Table 4-26.

Of particular note here is the smoking of fish which is done with fuelwood. This is considered a method of post-harvest food preservation and not a cooking FE demand. Fish smoking is done close to the site of fishing and done in mass quantities before passing to resellers or consumers for cooking or eating. Similar to this is drying of crops both with direct solar thermal energy and electric driers. Crops such as cocoa beans and shea tree seeds are dried in the open before sale. Fish are also dried in the open sun in large quantities much like smoking for preservation before sale and consumption.

Table 4-26 – Agriculture & Fishery: Shares of FE carrier demand disaggregated by FE service: Ghana 2008

FE Services	Share that FE service represents of FE carrier demand [%]				
	Fuelwood	Electricity	Diesel	Gasoline-Premix	Solar- thermal, direct
Smoking – fish	100				
Pumping		15	3.3		
Spraying - crops				9	
Lighting		15			
Refrigeration		25			
Milling		10			
Heat – poultry farms		10			
Sawing – small motors		10		1	
Drying – Fish & Crops		15			100
Transport – internal agriculture			6.7		
Transport – Large marine fishing vessels			45	45	
Transport – Small marine & freshwater fishing vessels			45	45	

(EC, 2014, 2006a)

The FE demand attributable to the energy services is calculated by the product of the total FE demand for each carrier and the share that each service represents in FE carrier demand as shown in Eq. 4-15.

$$Q^{Agr}_{i,s,y=0} = Q^{Agr}_{i,y=0} \times Share_{s,i,y=0} \ \ [ktoe] \qquad \textbf{Eq. 4-15}$$

Where:

$Q^{Agr}_{i,s,y=0}$: FE demand for FE carrier *i* attributable to FE service *s*, in year *y=0* [ktoe]

$Q^{Ser}_{i,y=0}$: Aggregate FE demand for FE carrier *i* in year *y=0* [ktoe]

$Share_{s,i,y=0}$: Share that FE service *s* represents of FE demand for carrier *i*, in year *y=0* [%]

The FEI for the Agriculture and Fishery sector is represented by the energy use per unit of GVA by the sector for each of the FE service-carrier combinations as in Eq. 4-10. The FEI per unit GVA allows for projection of FE demand together considering shifts in the mix of conversion technologies used in the sector and their respective energy efficiencies.

$$FEI^{Agr}_{i,s,y=0} = \frac{Q^{Agr}_{i,s,y=0}}{\omega_{i,s} \times GVA^{Agr}_{y=0}} \quad [ktoe/\text{monetary units}] \qquad \textbf{Eq. 4-16}$$

Where:

$FEI^{Agr}_{i,s,y=0}$: FEI at the energy service level for carrier *i* and service *s*, in year *y=0* [ktoe/monetary units]

$GVA^{Agr}_{y=0}$: GVA by the Service sector in the year *y=0* [monetary units]

$\omega_{i,s}$: Contribution to GVA of the sector for subsector *k*, carrier *i* and service s [%]

The share that energy consumption contributes to the total GVA of the sector was assumed to be 100%.

The resulting FE demand for each FE service-carrier combination is shown together with the corresponding FE intensity in Table 4-27.

Table 4-27 - Agriculture and fishery: FE demand for each service & carrier combination: Ghana 2008

FE service – carrier combination	FE Demand [ktoe]	FE Intensity [ktoe/US $]
Smoking – Fuelwood	16.41	2.48E-07
Pumping – Electricity	0.51	7.76E-09
Pumping – Diesel	2.45	3.70E-08
Spraying – crops –Gasoline Premix	10.02	1.51E-07
Lighting – Electricity	0.26	3.88E-09
Lighting outdoor – Electricity	0.26	3.88E-09
Lighting poultry house – Electricity	0.17	2.59E-09
Refrigeration – fishing –Electricity	0.34	5.17E-09
Refrigeration – post harvest –Electricity	0.51	7.76E-09
Milling – Electricity	0.34	5.17E-09
Heating – Electricity	0.17	2.59E-09
Sawing – Electricity	0.34	5.17E-09
Sawing – Gasoline Premix	1.11	1.68E-08
Drying – Electricity	0.51	7.76E-09
Drying – Solar thermal, direct	22.76	3.44E-07
Transport – Land-prep & harvest– Diesel	2.45	3.70E-08
Transport – Post harvest – Diesel	2.45	3.70E-08
Transport – Large marine fishing vessels – Diesel	33.05	4.99E-07
Transport – Large marine fishing vessels – Gasoline – Premix	50.09	7.57E-07
Transport – Small marine & freshwater fishing vessels – Diesel	33.05	4.99E-07
Transport – Small marine & freshwater fishing vessels – Gasoline – Premix	50.09	7.57E-07

calculations

4.7 PE supply and transformation considerations

As previously described in Section 4.5, the energy demand and supply model presented needed to be made compatible with data available for Ghana, and therefore it is a generic energy model built for the case considered rather than a completely generic model.

In an attempt to concretize the PE supply and transformation considerations, examples are provided for Ghana, the case study country. These values represent base year, y=0, data that are established with the modeling considerations made in this chapter, and are used as the input to the specific application of the model which is presented in detail in Chapter 5.

4.7.1 PE Supply

The required PES for imports is calculated as the total required PES that cannot be met by domestic PES in the case that domestic PES is available. In the case that domestic PES is not available, requirements are met through imports. This is the case for the majority of fossil fuels (e.g. crude oil and natural gas).

4.7.1.1 Crude oil - Imports

At the time of publishing the SNEP in 2006, the case study country of Ghana did not have any significant resources or production of domestic crude oil. While exploration and related activities were underway in 2006 no substantial crude oil resources had been confirmed, and the current work did not assume or model the possible discovery of domestic resources. Therefore 100% of crude oil was assumed to be imported and all crude oil was delivered to the Tema Oil Refinery (TOR) except for an insignificant quantity destined for thermal electricity generation units and not considered in this work as they were considered decommissioned by the base year 2008 (EC, 2006c). The imported crude oil is therefore equal to the required PES for the oil refinery as shown in Eq. 4-17.

$$PES_{crude\ oil,y}^{Imp} = PES_{crude\ oil,y}^{TOR}\ [ktoe] \qquad \textbf{Eq. 4-17}$$

Where:

$PES_{crude\ oil,y}^{Imp}$: PES imports of crude oil in year *y* [ktoe]

$PES_{crude\ oil,y}^{TOR}$: PES requirements for the TOR of crude oil, in year *y* [ktoe]

4.7.1.2 Petroleum products - Imports

The petroleum based FE carrier demand in a given year, *y*, that cannot be met by the domestic production in the oil refinery are considered to be imported. Imported petroleum products are considered PES. No constraints are placed on the imported capacity of petroleum products as this is assumed to be driven by the domestic demand.

$$PES_{petroleum,y}^{Imp} = Q_{i,y}^{total} - Production\ capacity_i^{TOR}\ [ktoe] \qquad \textbf{Eq. 4-18}$$

Where:

$PES_{petroleum,y}^{Imp}$: Imported PES for petroleum products, in year *y* [ktoe]

$Q_{i,y}^{total}$: Total FE demand for FE carrier *i* in corresponding year *y* [ktoe]

$Production\ capacity_i^{TOR}$: The annual production capacities for each output. See Table 4-29 [ktoe]

4.7.1.3 Natural gas - Imports

At the time of publishing the SNEP in 2006, Ghana did not have any significant domestic resources or production of natural gas. The current work did not assume or model the possible discovery of domestic natural gas resources. Therefore 100% of natural gas was assumed to be imported via the WAGP (EC, 2006c). The capacity of the WAGP was stated to be 460 Million standard cubic feet per day (MMSCFD) and serves the countries of Ghana, Benin and Togo with an origin in Nigeria (WAPCo, 2015).

Although the WAGP has a rated maximum capacity, no constraints were placed on imported natural gas in Ghana. Imports in the energy sector were used entirely for thermal electricity generation units. Allowing for imports to surpass this capacity in the model allowed for planners and policy makers to understand the PES requirements for a given EP alternative. Planners can make additional adjustments for electricity generation capacity. Imports from additional sources such as liquefied natural gas (LNG) via shipping vessels or potential domestic resources could be made to meet the calculated PES requirements.

The total PES import requirement for natural gas is then equal to the total PES requirement for natural gas thermal electricity generation in the same year, as shown in Eq. 4-19.

$$PES^{Imp}_{natural\ gas,y} = \sum_{g=1}^{W} PES_{natural\ gas,g,y}\ [ktoe] \qquad \textbf{Eq. 4-19}$$

Where:

$PES^{Imp}_{natural\ gas,y}$: PES imports of *natural gas* in year *y* [ktoe]

$PES_{natural\ gas,g,y}$: PES requirements of *natural gas*, for electricity generation unit g, in year *y* [ktoe]

4.7.1.4 Coal – Imports

The case study country, Ghana, to date does not have any domestic coal resources. The current work did not assume or model the possible discovery of domestic coal resources. PES of coal was therefore met entirely through imports.

The PES import requirement is equal to the total requirement of coal for electricity generation as coal is imported uniquely for electricity generation.

$$PES^{Imp}_{coal,y} = \sum_{g=1}^{W} PES_{coal,g,y}\ [ktoe] \qquad \textbf{Eq. 4-20}$$

Where:

$PES^{Imp}_{coal,y}$: PES imports of coal, in year *y* [ktoe]

$PES_{coal,g,y}$: PES requirements of *coal*, for electricity generation unit g, in year *y* [ktoe]

4.7.1.5 Electricity – Imports

The case study country, Ghana, is connected to the WAPP allowing for import and export of electricity through connections to neighboring countries. As of 2006 Ghana had three international power grid connections comprising a 225 kV line to the Ivory Coast and two 161 kV lines to Togo. Ghana is able to contract up to 225 MW from the Ivory Coast with an average annual import of 1,000 GWh of electricity. Imports are predominantly from the Ivory Coast and exports are majorly to Togo (EC, 2006b).

The FE demand for electricity that surpasses the domestic generation capacity is met through imports. The imports are calculated as the difference between the total FE demand for electricity and the installed domestic capacity as shown in Eq. 4-21. Exports are not considered in the current model (Section 4.7.1.8), and so they are not accounted for in this equation.

$$PES^{Imp}_{imported\ electricity,y} = Q^{total}_{electricity,y} - Annual\ Generation\ capacity_{electricity,y}\ \ [ktoe] \qquad \textbf{Eq. 4-21}$$

Where:

$PES^{Imp}_{imported\ electricity,y}$: The imported electricity, in the year *y* [ktoe]

$Q^{total}_{electricity,y}$: Total FE demand for electricity, considering transmission and distribution losses in year *y* [ktoe]

$Annual\ Generation\ capacity_{electricity,y}$: Domestic electricity generation capacity in year *y* [ktoe]

Although imports through the WAPP are constrained by the connections to neighboring countries these constraints are present in the model. This is to allow for planners to account for import necessities that surpass the domestic and import capacities. This can potentially be completed through additional future installed domestic capacity, additional international connections, or possibly DSM efforts. This necessity, however, does not arise in the case of the current model as supply side generation considerations are made based on FE demand for electricity.

4.7.1.6 Biomass – Domestic

PES requirements for biomass are driven by the FE demand for fuelwood in addition to the requirements for biomass to produce charcoal to meet FE demand for charcoal. Biomass PES is met through domestic resources in the model as import of woodfuel is not considered a viable sustainable option (EC, 2006e).

Although domestic supply capacity is constrained to the harvestable national stock of biomass, the model does not place any constraints on the PES of biomass. The total PES requirement for biomass is equal to the FE demand for fuelwood and the PES requirement of biomass for charcoal production. There is no conversion between the PES of biomass and the FE carrier of fuelwood as they are identical to each other.

$$PES_{biomass,y} = Q^{total}_{fuelwood,y} + PES^{charcoal}_{biomass,y} \ [ktoe] \tag{Eq. 4-22}$$

Where:

$PES_{biomass,y}$: Total PES requirement of biomass, in year *y* [ktoe]

$Q^{total}_{fuelwood,y}$: Total FE demand for fuelwood, in year *y* [ktoe]

$PES^{charcoal}_{biomass,y}$: Biomass PES requirement for production of charcoal, in year *y* [ktoe]

4.7.1.7 Renewables – Domestic

<u>Non-electricity generation supply</u>

The PES requirement of direct solar thermal (DST) energy is equal to the FE demand of the carrier for drying in the production of Agriculture and Fishery products (e.g. cocoa and fish). No losses are considered in the transformation of PE to FE in this transformation following the non-thermal renewable PE accounting considerations discussed in Section 4.3.1.

$$PES_{DST,y} = \frac{Q^{total}_{DST,y}}{\eta^{DST}} \ [ktoe] \tag{Eq. 4-23}$$

Where:

$PES_{DST,y}$: PES requirements of direct solar thermal energy (DST), in year *y* [ktoe]

$Q^{total}_{DST,y}$: FE demand for DST, in year *y* [ktoe]

η^{DST}: Efficiency of PE to FE transformation of DST energy, in this case $\eta^{DST} = 100$ [%]

<u>Electricity generation supply</u>

The PES requirements for domestic PE resources are driven by the requirements for electricity generation. Renewable electricity generation units consist of thermal and non-thermal generation technologies. The PES is calculated based on the total requirement for electricity generation detailed in the respective section as shown in Eq. 4-24.

The PES considered consists of hydro, wind, landfill gas, municipal solid waste, bio/wood waste, solar (PV), and marine energy.

$$PES_{r,y} = \sum_{g=1}^{W} PES_{r,g} \ [ktoe] \qquad \text{Eq. 4-24}$$

Where:

$PES_{r,y}$: PES of PE resource r, in year *y* [ktoe]

$PES_{r,g}$: PES requirements of resource r, for electricity generation unit g [ktoe]

4.7.1.8 Exports

Although the potential for energy exports (e.g. biomass, petroleum products or electricity) is plausible, the current model, considers only domestic PES and PES imports. No energy exports were considered in this model.

This consideration was made fundamentally on the observation that domestic energy system was not able to meet FE demand, and that exports imply a level of surplus energy supplies that did not exist. In the base year the installed electricity was not sufficient to meet FE demand. The TOR at full operating capacity was not able to provide for 100% of domestic petroleum product demands, and imports of petroleum products (e.g. LPG, kerosene, diesel and gasoline) were required to meet demand. In addition fuelwood and charcoal exports were constrained by regulations and considered insignificant (EC, 2006e).

The financial considerations that may drive the export of energy carriers such as petroleum products or fuelwood was also considered outside the scope of this work. In addition, modeling of exports based on the FE demand of neighboring countries required additional national energy modeling or regional (multiple countries) energy modeling considerations that were outside the scope of the current work.

4.7.1.9 Stocks

Strategic stocks of petroleum and petroleum products are generally made in energy statistics, and often employed in EP attributes or indicators to evaluate PE security.

For the current work, however, they were not required for the model or for the attributes used in the evaluation of the EP alternatives. In addition, the country studied in the case study, Ghana, had no crude oil stocks and limited stocks of petroleum products.

Therefore, crude oil and petroleum product stocks and stock changes were not included in the model. The TOR was the only PES requirement for crude oil, and demand for petroleum products were met through domestic production or imports. This assumes that any strategic stock was kept at a constant level to be used only in exceptional circumstances, and thus the model did not consider strategic stock variations.

4.7.2 Charcoal production

Charcoal is a secondary product produced from biomass primary energy resources. Production is a transformation process in which the input is biomass and the outputs are charcoal and losses (IEA, 2015b). The transformation technologies used in charcoal production consist majorly of kilns, of various complexities, and rudimentary earth mounds.

The total demand for charcoal, from the Residential and Service sectors, drives the production of charcoal. The annual PES of fuelwood destined for charcoal production is calculated with the FE demand of charcoal, share of charcoal production by the transformation technology, and the efficiency of the charcoal technology process. This is shown in Eq. 4-25.

$$PES_{biomass,y}^{charcoal} = \frac{Q_{charcoal,y} \times \sum_{f}^{Z} Share_{f,y}}{\eta_{f}^{charcoal}} \quad [ktoe]$$ **Eq. 4-25**

Where:

$PES_{biomass,y}^{charcoal}$: The PES of biomass for charcoal production in year y [ktoe]

$Q_{charcoal,y}$: FE Demand in year *y* for charcoal [ktoe]

$Share_{f,y}$: Share that technology *f=1, 2, 3, …, Z* represents in the transformation process in year *y* [%]

$\eta_{f}^{charcoal}$: Transformation efficiency in biomass to charcoal production of technology *f* [%]

The efficiency of the production process varies according to the transformation technology as well as the density and moisture content of the input. Larger yields are achieved with dry and dense biomass inputs as well as increased kiln sizes (Leach and Gowen, 1987).

Charcoal production in Ghana is predominantly done with the less efficient technology of rudimentary earth mounds, and the share of improved kiln use is insignificant.

Earth mounds consume 4-6 metric tons of biomass for 1 metric ton of charcoal produced (EC, 2006e). The low end and high ends are based on average dry wood from the forest regions and savannah regions respectively. The Energy Commission of Ghana estimated that the conversion efficiency of the transformation process is approximately 14%, as shown in Table 4-28 (EC, 2009a).

Table 4-28 – Charcoal transformation technologies and shares: Ghana 2008

Transformation technology	Share in transformation [%]	Efficiency [%]
Rudimentary earth mound	100	14
Generic kiln	0	25

References: (EC, 2013b, 2009a, 2006e)

4.7.3 Petroleum refining

Petroleum refineries convert crude oil, an input, into different fractions that are converted into usable products and then finally into blended finished products. The processes that a refinery conducts to convert crude oil to finished products are complex and specific to the crude oil characteristics and desired products. Products can consist of energy carriers as well as other non-fuel chemical and specialty products. The production of fuels, energy carriers, is the most important function of a refinery, and is the focus in this work (IEA, 2005). Refinery outputs include LPG, gasoline, diesel, jet & domestic kerosene, and refined fuel oil.

There are no generic refinery designs or modes of operation and they can differ based on a large number of characteristics (e.g. configurations, products, product mix, market, location and age, and applicable environmental regulations) (IEA, 2005).

The quantity of crude oil entering the refinery provides the resources for the products produced in the transformation processes. For the purposes of this model the refining process is modeled as a black box where a constrained quantity of crude oil is the input and the energy carriers produced are represented by product mix shares and an aggregated loss.

The TOR, originally constructed in 1961, is currently the only domestic oil refinery serving the country of Ghana. The refinery consisted of a crude oil distillation unit (CDU) with a production capacity of 28,000 bpd in 1990 which was expanded to 45,000 b/d in 2000. A residual fuel catalytic cracker (RFCC) with a capacity of 14,000 b/d was added to the refinery in 2002 allowing for residual fuel oil to be further refined increasing the outputs of products such as diesel, gasoline and LPG.

TOR capacity was cited in EC (2006c) to be 45,000 b/d or 16.425 million bbl per year when operating at 100% utilization. More recently, the EC (2013a) reported the capacity, at 100% utilization, to be approximately 13.915 million bbl per year. This more up to date value was used for the base year in this work together with the shares of products and losses cited, as shown in Table 4-29.

The capacity utilization of a refinery is a ratio of the real production and the maximum capacity for production. Capacity utilizations of 95% and higher are typically the target value to remain economically profitable. This value varies for the TOR year to year and the TOR was reported to be operating at approximately 78% in 2010 and 2011. This value dropped to 25% in 2012. The current model had a base year of 2008 and so the value from the years 2010 and 2011 were used. Unforeseen drops in the utilization capacity such as that in 2012 were considered unpredictable. However using a value such as 78% and not 95-100% was assumed to account for years with lower values (EC, 2012b).

In actuality the supply of crude oil to a refinery would be driven by the total demand for the various petroleum based FE carriers. However, demand has exceeded the production capacity of the TOR, and therefore the refinery was modeled with constant petroleum based outputs, losses, and crude oil inputs (EC, 2012b). The petroleum based FE carrier outputs from the TOR were constrained by maximum annual production capacities. FE demand exceeding domestic production capacities in a given year were considered to be imported and discussed in Section 4.7.1.2.

The PES required by the refinery to meet the demand for petroleum based FE carrier outputs is shown in Eq. 4-26.

$$PES^{TOR}_{crude\ oil,y} = \frac{\sum_i^M Q_i^{TOR}}{\eta_r^{refinery}}\ [ktoe] \qquad \textbf{Eq. 4-26}$$

Subject to:

$$0 \leq FEC^{TOR}_{petroleum,y} \leq Production\ capacity^{TOR}_{i,y}$$

Where:

$PES^{TOR}_{crude\ oil,y}$: Crude oil imports for TOR, in year y [ktoe]

Q_i^{TOR}: FE demand for carrier *i* supplied by the oil refinery [ktoe]

$\eta_r^{refinery}$: The efficiency of the oil refinery, for conversion of resource *r*, is calculated as $\eta_r^{refinery} = 1 - Share\ of\ losses$ [%]

$FEC^{TOR}_{petroleum}$: Petroleum based FE carrier outputs from the TOR for FE carrier *i* in year *y* [ktoe]

$Production\ capacity^{TOR}_{i,y}$: The annual production capacities for each output [ktoe]

Table 4-29 - Petroleum refining capacity TOR: Ghana 2008

Input	Refinery Capacity[1] [ktoe/year] (million bbl/year)	Operating Capacity [%]
Crude oil	2,018 (13.915)	78

Output	Share of total output [%]	Production Capacity[2] [ktoe/year]
Diesel	40.34	634.9
Gasoline[3]	30.22	475.5
Kerosene[4]	13.82	217.4
LPG	6.15	96.8
Refined fuel oil	3.44	54.2
Losses[5]	6.03	-

1. At full operating capacity
2. At stated operating capacity
3. Gasoline and gasoline premix
4. Aviation turbine & general kerosene
5. Losses, consumption & or non-fuel outputs

4.7.4 Electricity generation

Electricity generation is considered for electricity from the grid, minigrids and standalone systems. The FE demand carriers are disaggregated by generation system type to clearly account for the different generation systems used to provide electricity.

The Ghanaian Ministry of Energy instituted the National Electrification Scheme (NES) in 1989 with the goal of reaching 100% access to electricity in the 30 year period from 1990 to 2020 (Kemausuor et al., 2011). The NES provided the policy tools that enabled both urban areas and rural communities to connect to electricity supplies. The national electricity grid has been the predominant supplier of electricity for the majority of households with access to electricity in Ghana through the NES according to the EC (2006a). Recommendations have been made by the EC (2006b) to expand efforts to increase access to electricity to alternative sources of supply such as minigrids or standalone systems where applicable. The three options of national grid expansion, minigrids, and stand-alone systems are options considered in previous works in SSA for electricity supply in rural areas (Rosnes and Vennemo, 2009).

In the current work, electricity supply in urban and peri-urban areas will consist entirely of national grid access as the national grid has been extended to all major urban areas in the case study country (Kemausuor et al., 2011; EC, 2013a).

The technical solutions for electricity supply, and access, for rural electricity supply in the current work consist of the national electricity grid and the corresponding electricity generation mix, minigrids, which serve rural communities, and finally standalone systems, which serve a single household. The considerations for each technical solution are detailed in the sections that follow.

4.7.4.1 National grid

The PES for electricity generation is calculated with the share that each electricity generation technology type represents in the total installed capacity, the availability factor of the generation technology and the efficiency assumed. The total demand for electricity including transmission and distribution system losses drives the demand for PES.

$$PES_{r,y}^{elec\ gen} = Q_{electricity,y}^{total+TDL} \times \sum_{g}^{W} \frac{Share_{g,y}^{elec\ gen} \times Availability_{g}^{elec\ gen}}{\eta_{g,r}^{elec\ gen}} \quad [ktoe] \qquad \textbf{Eq. 4-27}$$

Where:

$PES_{r,y}^{elec\ gen}$: PES requirement, r, for electricity generation in year, y [ktoe]

$Q_{electricity,y}^{total+TDL}$: Total FE demand for FE carrier i, with transmission and distribution system losses (TDL) in year y [ktoe]

$Share_{g,y}^{elec\ gen}$: Share that technology g represents in the total installed capacity in year y [ktoe]

$Availability_{g}^{elec\ gen}$: Availability factor of electricity generation technology g [%]

$\eta_{r,g}^{elec\ gen}$: Efficiency of electricity generation technology g for conversion of resource r [ktoe]

The share that a generation technology g represents in the total electricity generation installed capacity is calculated as shown in Eq. 4-28. The national electricity generation technology considerations are shown in Table 4-30 for each transformation technology type.

$$Share_{g,y}^{elec\ gen} = \frac{\sum_{u}^{Y} Cap_{u,g,y}^{elec\ gen}}{\sum_{g}^{W} \sum_{u}^{Y} Cap_{u,g,y}^{elec\ gen}}\ [\%] \qquad \textbf{Eq. 4-28}$$

Where:

$\sum_{u}^{Y} Cap_{u,g,y}^{elec\ gen}$: Installed capacity of unit $u=1, 2, 3, \ldots, Y$ of generation technology $g=1, 2, 3, \ldots, W$ in year y [MW]

Table 4-30 – National electricity generation technology considerations: Ghana

Transformation technology	Technology index (g)	PE Supply index (r)	Efficiency [%]	Availability factor [-]
Oil	1	20	36	0.76
Coal	2	28	35	0.35
Gas turbine	3	26	36	Tapco & Tico: 0.75 Power barge & distributed turbines: 0.83 Mines Reserve: 0.76 Sunon Asogli: 0.68 Generic: 0.92
CCGT	4	26	57	Tema: 0.83 Takadori: 0.78 Generic: 88
Hydro – large	5	33	100	0.97
Hydro – small	6	35	100	1.00
Wind – onshore	7	34	100	0.22
Wind – offshore	8	34	100	0.22
Wind – small	9	36	100	0.22
Solar – PV plant	10	42	100	0.34
Solar – Concentrated	11	42	40	0.34
Solar – Standalone	12	42	100	0.34
Biogas – landfill	13	37	30	0.95
Solid waste – municipal	14	38	35	0.18
Biomass & wood waste	15	39	35	0.75
Diesel generator	16	55	36	1.00
Solar – PV plant -large	*17*	42	100	0.34
Wave	18	60	100	0.95
Tidal Barrage	19	60	100	0.98
Tidal Stream	20	60	100	0.95

(EC, 2006b; IEA, 2011b; IEA-ETSAP, 2010)
Availability factors are for generic technologies; values for specific installations are noted.

4.7.4.2 Minigrid

The PES for minigrid electricity generation systems was calculated based on the share that each electricity generation technology type represented in the mix of installed capacity and the technology efficiency. The minigrid electricity generation systems consisted of the common hybrid system of solar PV together with diesel generators. Availability for the minigrids generation units was assumed to be 100% as the diesel generator would provide power when solar PV was not available, and that 50% of the energy provided was provided by each of the technologies.

This was of course a simplification and minigrid generation systems could consist of different configurations depending on factors such as local renewable resources and proximity to petroleum based FE sources. For the current work a simplified common system is used for all applications of minigrids as it was not in the scope of this work to determine the resources available to each of the individual communities.

The total demand for electricity drives the demand for PES as shown in Eq. 4-29. No losses for the distribution of electricity in the minigrids were assumed due to the small size of minigrids and proximity of the generation units to the demand. In addition, non-technical losses were assumed to be insignificant due to limited number of customers and proximity of technical operators and authorities to the system.

$$PES_{r,y}^{M\ elec\ gen} = Q_{electricity,y}^{total\ minigrid} \times \sum_{g}^{W} \frac{Share_{g,y}^{M\ elec\ gen}}{\eta_{g,r}^{M\ elec\ gen}}\ [ktoe] \qquad \textbf{Eq. 4-29}$$

Where:

$PES_{r,y}^{M\ elec\ gen}$: PES resource requirement, *r*, for electricity generation for minigrids (*M*) in year, *y* [ktoe]

$Q_{electricity,y}^{M\ total}$: Total FE demand for minigrid (*M*) supplied electricity, in year *y* [ktoe]

$Share_{g,y}^{M\ elec\ gen}$: Share that technology *g* represents in the minigrid generation mix in year *y* [%]

$\eta_{g,r}^{M\ elec\ gen}$: Efficiency of minigrid electricity generation technology *g=1, 2, 3…, W*, in conversion of resource *r* [%]

4.7.4.3 Standalone

The standalone electricity generation systems consisted solely of solar PV panels installed at the household level. The PES for standalone electricity generation systems as calculated based on the efficiency of the solar PV technologies.

The total demand for electricity was assumed to drive the demand for PES. The PES requirements were based solely on the conversion efficiencies of the solar panels.

$$PES_{r,y}^{S\ elec\ gen} = \frac{Q_{i,y}^{total}}{\eta_{g,r}^{S\ elec\ gen}} \quad [ktoe] \qquad \textbf{Eq. 4-30}$$

Where:

$PES_{r,y}^{S\ elec\ gen}$: PES resource requirement, *r*, for electricity generation for standalone systems (S) in year, *y* [ktoe]

$Q_{electricity,y}^{S\ total}$: Total FE demand for standalone systems (*S*) supplied electricity, in year *y* [%]

$\eta_{g,r}^{S\ elec\ gen}$: Efficiency of standalone electricity generation technology g, in conversion of resource *r* [%]

4.7.5 Transmission and distribution system

Electrical energy generated in the aggregated electricity generation system, consisting of various generation technologies, is delivered to demand via the electricity grid. The electricity grid consists of two main systems. First is the transmission system which transfers high-voltage electricity from the generation systems to regional substations. Second is the electricity distribution system which then delivers electricity to demand.

4.7.5.1 Stock - Transmission and distribution system

The transmission and distribution system was modeled for considerations within two dimensions. The first dimension was the measurement of the attribute of total cost of the installation and maintenance of the transmission and distribution system which grows together with FE demand (as described in Chapter 3). The second dimension was the measurement of the losses attributable to the transmission and distribution system.

The transmission and distribution system stock in the base year of 2008 is presented in Section 5.7.5, with considerations for Part I of the case study.

4.7.5.2 Losses - Transmission and distribution

Total losses in the electricity grid are attributable to two components. The first component is technical which consists of natural losses in the system predominantly resulting from power dissipation in components of the system such transmission and distribution lines, transformers, and measurement systems. The second component is non-technical, or soft, losses. These losses are caused by factors considered external to the power system and were considered in the current work to consist of electricity theft (World Bank, 2009).

The national electricity grid was modeled as a simplified “black-box” in which the energy from the electricity generation system was the input and the output was energy delivered to demand considering effective losses from the transmission and distribution systems. The total

FE demand and the expected losses therefore determined the electrical energy input required from the aggregated electricity generation system, see Eq. 4-31.

$$Q_{electricity,y}^{total+TDL} = \frac{Q_{electricity,y}^{total}}{\left(1 - Loss_y^{trans}\right) \times \left(1 - Loss_y^{dist}\right)} \;\; [ktoe] \qquad \textbf{Eq. 4-31}$$

Where:

$Q_{elecicity,y}^{total+TDL}$: Total FE demand of electricity, with transmission and distribution system losses (TDL) in year *y* [ktoe]

$Q_{electricity,y}^{total}$: Total FE demand for of electricity, from the FE demand sectors in year *y* [ktoe]

$Loss_y^{trans}$: Effective losses resulting from the transmission system in year *y* [%]

$Loss_y^{dist}$: Effective losses resulting from the distribution system in year *y* [%]

The transmission and distribution system losses used for the case study country, Ghana, are shown in Table 4-31. The transmission system losses consisted principally of technical losses. The distribution system losses are composed of technical and non-technical losses. Of the total distribution system losses technical losses account for 11-15 percentage points and the remaining losses are attributed to non-technical losses (EC, 2014, 2006b).

Table 4-31 – Electricity transmission and distribution system losses: Ghana 2008

System type: Electricity grid	Losses [%]
Transmission	3
Distribution	26

Reference: (EC, 2006b)

4.8 Reference projection development

To develop a reference projection as well as policy alternatives a method was required which allowed for projections of the energy demand and supply modeling considerations along the planning horizon. In the current work the FE demand sectors were assumed to drive the demand for FE carriers, which in turn drove the transformation processes, and the PE supply requirements.

Given the specificities that exist within each demand sector the methods varied depending on the driving measure of activity level, however the general form follows that presented previously in Eq. 4-1.

4.8.1 Residential sector projections

The total FE demand is calculated as the sum for all population types and FE carrier and service combinations as shown in equation Eq. 4-32. The FE demand in the Residential sector is driven by the number of households that have access to each respective energy carrier in the different population types, as depicted in Eq. 4-33. FE demand is then the product of these considerations and the FE intensity and the level of ownership of appliances, Eq. 4-34.

$$Q_y^{Res} = \sum_{p=1}^{3}\sum_{i}^{M}\sum_{s}^{P} Q_{p,i,s,y}^{Res} \quad [ktoe] \qquad \textbf{Eq. 4-32}$$

$$Q_{p,i,s,y}^{Res} = FEI_{p,i,s,y}^{Res,\ app} \times Access_{\ p,i,y} \times HHS_{p,y} \times Own_{p,i,s,y} \quad [ktoe] \qquad \textbf{Eq. 4-33}$$

Where:

Q_y^{Res}: Total FE demand in the Residential sector in year *y* [ktoe]

$Q_{p,i,s,y}^{Res}$: FE demand from population type p for FE carrier *i=1, 2, 3, …, M*, attributable to FE service *s=1, 2, 3, …, P,* in year *y* [ktoe]

$Access_{\ p,i,y}$: Share of households of population type *p* that have access to carrier *i* [%]

$FEI_{p,i,s,y}^{Res,\ app}$: The FE intensity per unit of appliance (e.g. appliance or technology) for population type p for FE carrier i attributable to FE service *s*, in year y for each sector *j*, and subsector *k* when applicable [ktoe/appliance]

$HHS_{p,y}$: Households of population type *p,* in year *y* [household]

$Own_{p,i,s,y}$: Level of ownership of units at the household level for population type *p* for FE carrier *i* attributable to FE service *s*, in year *y* [appliance/household]

The FEI is assumed to vary with changes in the representative end-use technology mix from the base year to the year of the projection as in Eq. 4-34. The FE intensity is expressed per appliance in the Residential sector and per unit GVA at the sector level for the remaining productive sectors.

$$FEI_{p,i,s,y}^{Res,\ app} = FEI_{p,i,s,y=0}^{Res,\ app} \times \frac{\left(Rep_{i,s,y}^{Res,\ app} - Rep_{i,s,y=0}^{Res,\ app}\right)}{Rep_{i,s,y=0}^{Res,\ app}} \quad [\frac{\text{ktoe}}{\text{appliance or GVA}}] \qquad \textbf{Eq. 4-34}$$

Where:

$Rep_{p,i,s,y}^{Res,\ app}$: Representative efficiency of the end-use technology mix for the FE service *s* - carrier *i* combination in year *y*, and population type *p* [%]

Each FE service-carrier combination has a unique representative end-use appliance mix of the appliances used to provide the given FE service. The representative efficiency of each FE carrier and service combination was calculated from the mix of end-use appliances as shown in Eq. 4-35. This assumed a share for each technology present in the total mix of technologies that were employed in this FE carrier and service combination and its respective end-use efficiency. In this manner, a representative efficiency was established for FE demand for a generic “appliance” referred to here as a representative efficiency.

$$Rep_{p,i,s,y}^{Res,\ app} = \sum_{z=1}^{H} \eta_{z,i,s}^{end} \times Share\ _{z,i,s,y}^{Res} \quad [\%] \qquad \textbf{Eq. 4-35}$$

Where:

$\eta_{z,i,s}^{end}$: The end-use efficiency of appliance type z, energy carrier i, and FE service s [%]

$Share\ _{z,i,s,y}^{Res}$: Represents the share that technology z represents in the mix of appliances, $z=1$, 2, 3, ..., H, that provide FE service s for the respective carrier i, in year y [%]

Ownership levels were estimated for the base year of 2008, and are presented with the case study details in Table 5-9.

When data is accessible ownership levels are commonly modeled in an S-shaped curve which can be modeled with a Gompertz curve (Riedy, 2005; Haydt, 2012). Use of the curve requires fitting data on historic appliance introduction into the market. Other alternatives to model ownership or stock levels of appliances include stock models which consider the stock of appliances being used and their lifetimes and can also include considerations of sales of new appliances (Riedy, 2005). These, however require detailed data about appliance ownership which was not deemed available in the current context.

When data is not available, as in the current case, ownership levels can be frozen over the planning horizon or a proxy value to develop ownership levels can be used. For the years following 2008 in the planning horizon ownership levels, appliances per household, can be assumed to grow in relation to the change in GDP/capita of the case study country.

$$Own_{p,i,s,y} = Own_{p,i,s,y=0} \times \frac{GDP/capita\ _{y}}{GDP/capita_{y=0}} \quad [\text{appliance/household}] \qquad \textbf{Eq. 4-36}$$

Where:

$Own_{p,i,s,y}$: Level of ownership of units at the household level for population type y for FE carrier i attributable to FE service s, in year y [appliance/household]

$GDP/capita\ _{y}$: is the GDP per capita at the national level for year y [monetary units/capita]

4.8.2 Service sector projections

The driving activity level variable in the Service sector is the GVA at the sector level. Calculation of the FE demand in the sector is calculated as the product of this activity level and the FE intensity of the sector through rearrangement of Eq. 4-10.

$$Q_{i,s,y}^{Ser} = FEI_{i,s,y}^{Ser} \times \omega_{i,s} \times GVA_{y}^{Ser} \quad [ktoe] \qquad \textbf{Eq. 4-37}$$

Where:

$Q_{i,s,y=0}^{Ser}$: FE demand for FE carrier *i* attributable to FE service *s*, in year *y=0* [ktoe]

$FEI_{i,s,y}^{Ser}$: FEI at the energy service level for carrier *i* and service *s* for the Service sector, in year *y* [ktoe/monetary units]

GVA_{y}^{Ser}: GVA by the Service sector in the year *y* for [monetary units]

$\omega_{i,s}$: Contribution to GVA of the FE service *s* and FE carrier *i* [%]

The FEI, as in the Residential sector, was assumed to vary with changes in the representative end-use technology mix from the base year to the year *y* as following Eq. 4-38 and Eq. 4-39. The FEI was expressed in ktoe per unit GVA at the sector level.

$$FEI_{i,s,y}^{Ser} = FEI_{i,s,y=0}^{\ app} \times \frac{\left(Rep_{i,s,y}^{Ser,app} - Rep_{i,s,y=0}^{Ser,\ app}\right)}{Rep_{i,s,y=0}^{Ser,\ app}} \quad \left[\frac{\text{ktoe}}{\text{appliance or GVA}}\right] \qquad \textbf{Eq. 4-38}$$

Where:

$FEI_{i,s,y}^{Ser}$: FEI at the energy service level for carrier *i* and FE service *s* for the Service sector, in year *y* [ktoe/monetary units]

$FEI_{i,s,y=0}^{app}$: FEI per unit of appliance (e.g. appliance or technology) at the energy service level for carrier *i* and service *s*, in year *y* [ktoe/appliance]

$Rep_{i,s,y}^{Ser,\ app}$: Representative efficiency of the end-use technology mix for the FE service *s* - carrier *i* combination in year *y*, calculated for the Service sector, [%]

$$Rep_{i,s,y}^{Ser\ \ app} = \sum_{z=1}^{H} \eta_{z,i,s}^{end} \times Share\ _{z,i,s,y}^{Ser} \quad [\%] \qquad \textbf{Eq. 4-39}$$

Where:

$\eta_{z,i,s}^{end}$: The end-use efficiency of appliance type *z*, energy carrier *i*, and FE service *s* [%]

$Share\ ^{Ser}_{z,i,s,y}$: Represents the share that technology z represents in the mix of appliances, z=1, 2, 3, ..., H, that provide FE service *s* for the respective carrier *i* in the Service sector and year *y* [%].

4.8.3 Industry sector projections

The Industry sector like the Service sector is a productive sector and the driving activity level is the GVA at the sector level. The FE demand at the sector level is then calculated as the product of this activity level and the FE intensity by rearranging Eq. 4-12.

$$Q^{Ind}_{k,i,s,y} = FEI^{Ind,k}_{i,s,y} \times \omega_{k,i,s} \times GVA^{Ind}_{y} = \quad [ktoe] \qquad \textbf{Eq. 4-40}$$

Where:

$Q^{Ind}_{k,i,s,y}$: FE demand for FE carrier i attributable to FE service *s* in subsector *k* of the Industry sector in year y [ktoe]

$FEI^{j,k}_{i,s,y}$: FEI at the energy service level for carrier *i* and service *s* for Industry sector, and subsector *k*, in year *y* [ktoe/monetary units]

GVA^{Ind}_{y}: GVA of the Industry sector in the year *y* [monetary units]

$\omega_{k,i,s}$: Contribution to GVA in subsector *k, for* carrier i, attributable to FE service *s* [%]

The FEI was evaluated with the representative end-use technology mix from the base year to the year *y* as following Eq. 4-41 and Eq. 4-42. The FEI was expressed in ktoe per unit GVA at the sector level.

$$FEI^{Ind,k}_{i,s,y} = FEI^{Ind,k,\ app}_{i,s,y=0} \times \frac{\left(Rep^{Ind,k,\ app}_{i,s,y} - Rep^{Ind,k,\ app}_{i,s,y=0}\right)}{Rep^{Ind,k,\ app}_{i,s,y=0}} \quad \left[\frac{\text{ktoe}}{\text{appliance or GVA}}\right] \qquad \textbf{Eq. 4-41}$$

Where:

$Rep^{Ind,k,\ app}_{i,s,y}$: Representative efficiency of the end-use technology mix for the FE service *s* – carrier *i* combination in year *y*, calculated at for each Industry sector, and subsector *k* [%]

$FEI^{Ind,k,\ app}_{i,s,y=0}$: FEI per unit of appliance (e.g. appliance or technology) at the energy service level for carrier *i*, service *s*, in the Industry sector and subsector *k*, in year *y* [ktoe/appliance]

$$Rep^{Ind,k,\ app}_{i,s,y} = \sum_{z=1}^{H} \eta^{end}_{z,i,s} \times Share\ ^{Ind,k}_{z,i,s,y} \quad [\%] \qquad \textbf{Eq. 4-42}$$

Where:

$\eta^{end}_{z,i,s}$: The end-use efficiency of appliance type *z*, energy carrier *i*, and FE service *s* in sector *j*, and subsector *k* [%]

$Share\ _{z,i,s,y}^{Ind,k}$: Represents the share that technology z represents in the mix of appliances, z=1, 2, 3, ..., H, that provide FE service *s* for the respective carrier *i* in the Industry sector, and subsector *k*, in year *y* [%]

4.8.4 Transport sector projections

The activity levels that drive FE demand within the Transport sector are the pkm and tkm for the passenger and freight mobility respectively. FE demand is then calculated as the product of this activity level and the FEI of the sector.

$$Q_{k,i,s,y}^{Tran} = FEI_{i,s,y}^{Tran,k} \times Mobility_{k,i,q,y} \quad [ktoe]$$ **Eq. 4-43**

Where:

$Q_{k,i,s,y}^{Tran}$: FE demand for FE carrier *i* attributable to FE service *s* in subsector *k* of the Transport sector in year y [ktoe]

$FEI_{i,s,y}^{Tran,k}$: FEI at the energy service level for carrier *i* and service *s* for the Transport sector, and subsector *k*, in year *y* [ktoe/pkm or ktoe/tkm]

Mobility, following the base year was expected to grow at the rate that was stipulated in the SNEP from Ghana which is detailed further in Section 5.6.4 for the case study (EC, 2006d). Calculation of the mobility is then expressed as the product of the base year mobility and the change in percentage from the base year as in Eq. 4-44.

$$Mobility_{k,i,q,y} = Mobility_{k,i,q,y=0} \times \Delta\mathrm{Mobility}_{\ y} \quad [pkm\ or\ tkm]$$ **Eq. 4-44**

Where:

$Mobility_{k,i,q,y}$: The mobility for subsector *k* and FE carrier *i* for either passenger (q=1) or freight (q=2) in year *y* [pkm or tkm]

$\Delta\mathrm{Mobility}_{\ y}$: The percentage change in mobility levels from the base year as expressed in the SNEP until year *y* [%]

4.8.5 Agriculture and Fishery sector projections

The Agriculture and Fishery sector is represented as a productive sector in which FE demand is driven by the GVA at the sector level. FE demand is calculated as the product of the FEI and the GVA.

$$Q_{k,i,s,y}^{Agr} = FEI_{k,i,s,y}^{Agr} \times \omega_{i,s} \times GVA_{y}^{Agr} = \quad [ktoe]$$ **Eq. 4-45**

Where:

$Q_{i,s,y}^{Agr}$: FE demand for FE carrier *i* attributable to FE service *s* of the Agriculture and Fishery sector, in year *y* [ktoe]

$FEI_{i,s,y}^{Agr}$: FEI at the energy service level for carrier *i* and service *s*, for the Agriculture and Fishery sector, in year *y* [ktoe/monetary units]

GVA_{y}^{Agr}: GVA by the Service sector in the year *y*, for the Agriculture and Fishery sector [monetary units]

$\omega_{i,s}$: Contribution to GVA *for* carrier *i*, attributable to FE service *s* [%]

The FEI is evaluated with the representative end-use technology mix from the base year to the year *y* as following Eq. 4-46 and Eq. 4-47. The FEI is expressed in ktoe per unit GVA at the sector level.

$$FEI_{i,s,y}^{Agr} = FEI_{i,s,y=0}^{Agr,\ app} \times \frac{\left(Rep_{i,s,y}^{Agr,\ app} - Rep_{i,s,y=0}^{Agr,\ app}\right)}{Rep_{i,s,y=0}^{Agr,\ app}} \quad \left[\frac{\text{ktoe}}{\text{appliance or GVA}}\right] \qquad \textbf{Eq. 4-46}$$

Where:

$FEI_{i,s,y=0}^{Agr,\ app}$: FEI per unit of appliance (e.g. appliance or technology) at the energy service level for carrier *i* and service *s*, in the Agriculture and Fishery sector, in year *y* [ktoe/appliance]

$Rep_{i,s,y}^{Agr,\ app}$: Representative efficiency of the end-use technology mix for the FE service, *s* carrier *i* combination in year *y*, calculated in the Agriculture and Fishery sector [%]

$$Rep_{i,s,y}^{Agr,\ app} = \sum_{z=1}^{H} \eta_{z,i,s}^{end} \times Share\ _{z,i,s,y}^{Agr} \quad [\%] \qquad \textbf{Eq. 4-47}$$

Where:

$\eta_{z,i,s}^{end}$: The end-use efficiency of appliance type *z*, energy carrier *i*, and FE service *s* in the Agriculture and Fishery sector [%]

$Share\ _{z,i,s,y}^{Agr}$: Represents the share that technology z represents in the mix of appliances, *z=1, 2, 3, ..., H*, that provide FE service *s* for the respective carrier *i* in the Agriculture and Fishery sector, in year *y* [%].

4.8.6 PE supply and transformation projections

The energy supply projection was driven by FE demand. The projection of the FE demand for each year *y* was then assumed to drive the transformation processes and the required PE supply. The equations within Section 4.5 therefore apply to all years within the planning horizon.

Chapter 5

Case study part I – National energy system modeling

Application of national energy planning methodology

5.1 Purpose of the case study

The current chapter presents a case study conducted for Ghana to implement the national EP methodology in a real world application and to address the third and final research question of the work[15]:

> *How do the results from an EP methodology including these additional objectives differ from those from a methodology including solely the base objectives?*

The results and conclusions drawn from the case study provide the information necessary to answer the research question within the context of the current work. The results and conclusions are not necessarily universally applicable, but provide an initial understanding of the applicability of the national EP methodology developed, and importantly a test of the hypothesis of the current work.

The case study consisted of three main phases following the national EP methodology presented in Chapter 3. The first phase, or problem structuring phase was previously presented in Sections 3.5 and 3.6. The current chapter (Part I of the case study) details the application of the energy system model to the case study country, the Reference Projection and EP alternatives. Chapter 6, which follows, describes part II of the case study. This consists of the MCDA evaluation of the EP alternatives.

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[15] The research questions are presented in Section 1.2.

The development of the Case Study was supported by a period abroad from September 2014 to February 2015 at The Energy Center (TEC) at Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana. The period abroad provided the opportunity to verify energy modeling assumptions, receive comments and feedback on the MCDA model, establish contacts with energy sector actors and DMs, and finally to conduct a DC during which EP alternatives were evaluated with energy sector DMs in Ghana.

5.2 Choice of case study country

The motivation for selecting Ghana as the case study country from the ECOWAS region was based on a number of considerations. The first was the stable national situation which was conducive to an extended site visit. Second was the national interest in EP efforts which were identified in the literature review presented in Chapter 2. Third, was the accessibility of reliable data that was available from previous national EP efforts and the agencies responsible for aggregation of energy data and EP efforts (i.e. the EC). A recent energy plan, the SNEP would also provide for a basis of comparison as results of the methodology developed in the current work could be compared to those recommended in the energy plan. Fourth was the availability of in-country contacts at an energy research center, TEC at KNUST in Kumasi, Ghana which extended an invitation as a host institute for an extended site visit. Finally, and possibly most important was the interest shown in the current work by both the TEC and EC. This interest in the work was important as it was not commissioned work.

5.3 Description of Ghana in the context of the case study

The country of Ghana has a total surface area of 238,533 km^2 which is similar to the size of the United Kingdom (UN, 2015a). The country borders the Gulf of Guinea and has a predominantly tropical climate; however the regions vary and the north can be described as hot and dry, the southeast is warm and relatively dry, and the southwest is hot and humid (CIA, 2015). The total population was approximately 25.37 million in 2012. The population living in urban areas was estimated at 53% (UN, 2015a).

The capital of Ghana and the largest city in terms of population and size is Accra, located in the southwest coast. The second largest city is Kumasi, located in the central "*greenbelt*" Ashanti region. The country is divided into ten administrative regions, shown with regional capitals in Figure 5-1.

The gross domestic product in 2014 was 38.6 million US $ and the annual growth rate was 4.2% (World Bank, 2015a). The total public debt to GDP ratio was at 49% in 2013 (MoF, 2015). The GDP per capita in 2014 was 1,461 US $. In terms of development the Human Development

Index for Ghana was ranked 135th out of 187 countries within the medium human development category.[16]

Figure 5-1 - Ghana map with administrative regions & local government seats (Natural Earth, 2014)

The GVA by the Industry, Service, and Agriculture sectors of the country were 30%, 49% and 21% (share of GDP) respectively in 2014 (UN, 2015a). The major agricultural products include cocoa, rice, cassava, peanuts, corn, shea nuts, bananas and timber. The key industries are mining (gold), lumbering, light manufacturing, aluminum smelting, food processing, cement, small ship building and petroleum extraction (CIA, 2015). The largest exports (value) from these industries in 2013 were gold, petroleum, and cocoa beans (UN, 2015b). Ghana began to export petroleum in large quantities only recently in 2011. According to the national account statistics the largest share of the Service sector (share of value added) in 2013 was transportation 23% (Transportation was considered to be a separate sector in the current work) followed by public administration services 14% and financial and insurance activities 13% (GSS, 2014).

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[16] The Human Development Index (HDI) was introduced in more detail in Chapter 1.

5.3.1 Previous and current EP and policy efforts in Ghana

Prior to Ghana's independence in 1957 the Gold Coast colonial administration maintained a diesel generation station, which was not built to provide access to the greater population (Botchway, 2000). In 1920 the Electricity Supply Ordinance was passed making the Electricity Department the state regulatory agency responsible for overseeing private diesel-based power generation. Owing to a lack of private sector involvement, it came to monopolize all power generation, transmission and distribution in the country (Botchway, 2000; Kemausuor et al., 2011).

In 1965 the first phase of the Akosombo hydro-electric dam construction was completed with a total capacity of 588 MW and later expanded to 912 MW in the 1970s. The dam was part of a government project which established the Volta River Authority (VRA) responsible for the generation and transmission of power. The primary, and largest, client of the VRA was the Volta Aluminum Company (VALCO) (Kemausuor et al., 2011).

Effort to increase energy access rates began with what has been described as a rural development policy in the early 1970s which also encompassed rural electrification activities (Botchway, 2000; Kemausuor et al., 2011). The National Electrification Scheme (NES) enacted in 1990 had the goal to reach 100% electrification by the year 2020. The NES, as well as the Self-Help Electrification Program (SHEP) which also was started in the early 1990s, promoted access through national grid extension (EC, 2013a, 2006a). As of 2011 all national and regional capitals were connected to the national grid (EC, 2013a). These programs faced many challenges due to the actualities in rural grid extension, including low income levels, low density of consumer demand in rural areas, and large distances between demand centers.

According to Kemausuor et al. (2011) attention was turned to the increasing demand for biomass for cooking in the 1900s. This prompted efforts to introduce improved cookstoves with the Improved Cookstove Project as well as alternative FE carriers such as charcoal, LPG, and biogas with the Improved Charcoal Making project, Biogas Project, and National LPG Promotion Programme respectively.

The first national EP effort was undertaken in 1985 by the National Energy Board (NEB). The NEB was later absolved in 1991, and up until the end of the 1990s a majority of the policy directions taken were "ad-hoc and stop-gap" measures (Kemausuor et al., 2011). Following a power crises in the years 1997 and 1998 a push was made to develop a comprehensive strategic plan for national energy sector development as well as a commission responsible for planning (EC, 2006d).

The Energy Commission of Ghana completed the first national energy master planning effort, the Ghana Strategic National Energy Plan (SNEP), in 2006 (EC, 2006a). The SNEP provided a strategic medium term plan for the supply and provision of energy to support development.

The SNEP, however, was never formally adopted by the government within official policies. The EC have continued their efforts, however, and the development of an updated SNEP is currently being undertaken (EC, 2014).

The Energy for Poverty Reduction Action Plan (EPRAP), not officially adopted, promoted efforts to ensure the reliable supply of electricity for health and other social services. It also promoted modern energy provision and energy for productive purposes for rural communities and clean modern cooking facilities (Kemausuor et al., 2011).

The National Energy Policy, adopted in 2009, outlined a national strategy to ensure secure and reliable high quality energy services for the population in Ghana as well as the productive sectors to meet development goals (MoE, 2009a).

Recent efforts consist of the Ghana Sustainable Energy for All Action Plan, developed in 2012 in response to the United Nations' Sustainable Energy for All (SE4ALL) Accelerated Framework. The action plan was a country specific strategy to reach the three SE4ALL "objectives" of (1) ensuring universal access to modern energy services, (2) doubling the global rate of improvement of energy efficiency, and (3) doubling the share of renewable energies in the global mix (EC and MoE, 2012).

At the regional (multi-country) level, the ECOWAS has set ambitious targets for access to modern cooking fuels, energy for productive purposes, and individual electricity supplies by the year 2015 (UEMOA and ECOWAS, 2006). ECOWAS countries, under the recent Energy Efficiency Policy and Renewable Energy Policy have been encouraged to develop national action plans and measures in response to regional energy targets set for the year 2030 (ECREEE, 2013a).

5.3.2 Overview of the national energy system - Ghana

The organizational structure of the national energy system in Ghana is headed by the public Ministry of Energy (MoE), which is responsible for enacting energy policies. A set of regulatory agencies have been established to ensure the healthy functioning of the energy sector. Under the auspices of the MoE, the Energy Commission of Ghana (EC) conducts EP efforts and serves as a policy advisor. The EC also acts as a regulatory agency for the development and use of energy resources in Ghana. The Public Utilities and Regulatory Commission (PURC) was established to regulate energy tariffs as well as to develop customer service regulatory frameworks. The National Petroleum Authority (NPA) oversees petroleum product import and export as well as refining activities at the TOR.

Petroleum products are primarily distributed and sold within Ghana by private companies, however prices are regulated by the NPA (IAEA, 2012).

In 1994 the government undertook energy sector restructuring efforts to improve operational efficiency and increase consumer access. The electricity generation, petroleum importing, petroleum refining, and petroleum product sales activities have been liberalized in an effort to improve competition. Within this effort the electricity sector, shown in Figure 5-2, was restructured to form a wholesale electricity market overseen by PURC. The electricity sector consists of multiple electricity generation companies including the VRA and other independent power producers. The Ghana Grid Company (GridCo) is responsible for the transmission system, which imports and exports electricity to regional neighbors and provides electricity to the distribution systems. Electricity distribution is overseen by two companies; the Electricity Company of Ghana (ECG) and the Norther Electricity Department (NED). There are plans to consolidate these into a single company. The distribution systems and GridCo provide to both bulk customers such as VALCO and regular market customers (Kemausuor et al., 2011; IAEA, 2012).

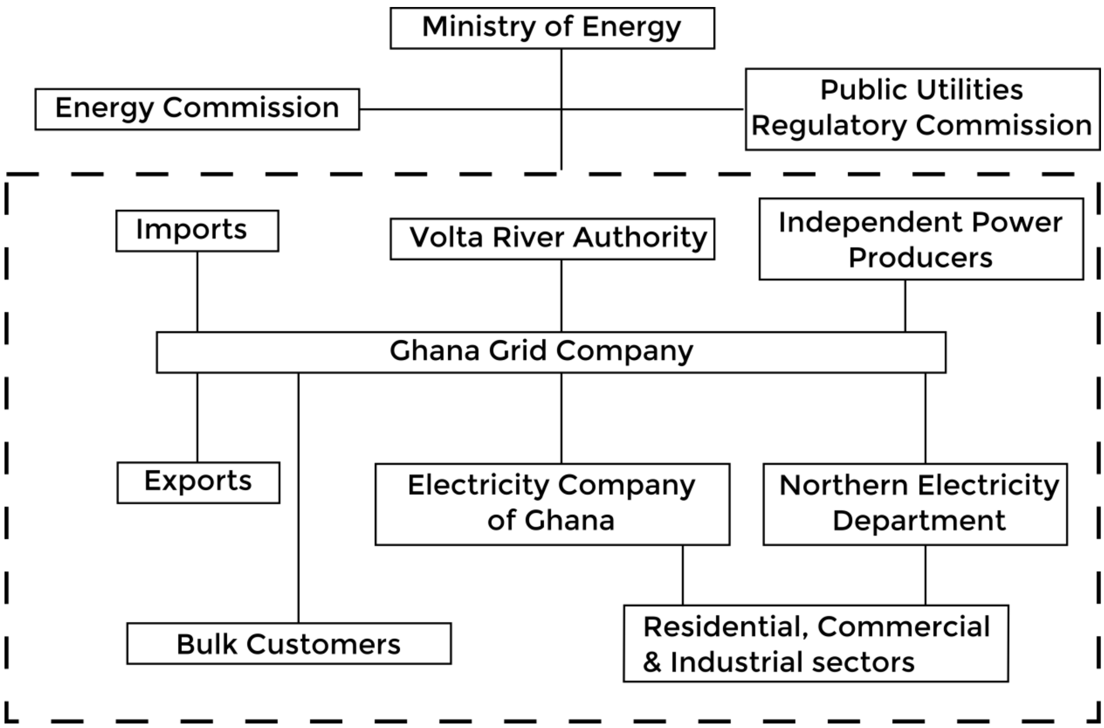

Figure 5-2 - Ghana electricity sector structure. Figure adapted from IAEA (2012) and Kapika and Eberhard (2013)

Ghana, as a member of the WAPP, has import and export connections with neighboring countries. It also has a connection to the WAGP which provides natural gas originating in Nigeria. The WAGP and the WAPP were previously described in Sections 4.7.1.3 and 4.7.1.5 respectively.

Beyond the actors that are directly involved in the energy sector at the government, regulator, and utilities levels a number of other stakeholders have interests in the sector. These actors represent a diverse set of often conflicting major concerns. Table 5-1 presents an overview of the main types of stakeholders in the energy sector of Ghana, their major concerns, and a list of in-country example stakeholders.

Table 5-1 – Energy sector stakeholders: Ghana

Stakeholder	Major concerns	Representatives in Ghana
Government	- Energy sector expansion in support of development goals - Security of PE Supply - Energy Access and affordability for population - Reliability of FE supply - Environmental protection	- Ministry of Energy (MoE) - Ministry of Power (MoP) - Ministry of Environment Science Technology & Innovation (MESTI)
Regulators	- Reliability of FE supply - Energy costs - Safety - Health	- Energy Commission of Ghana (EC) - PURC - NPA
Utilities	- Reliability of energy supplies - Provision of affordable services - Increased efficiency of services - Collection of payments from billed customers	- Energy Company of Ghana (ECG) - GridCo - VRA - NED - IPPs
Rate-payers, customers, & Residents	- Energy tariffs - Local environmental impact	- Association of Ghana Industries - Ghana Chamber of Mines - VALCO - General rate-payers - Private companies
Non-governmental Organizations (NGO), Environmental, & advocacy groups	- Local environmental impact - Health ramifications - Access to energy - Human development	- Environmental Protection Agency (EPA), Ghana - Agricultural and Rural Development Association, Ghana - Kumasi Institute of Technology, Energy and Environment (KITE) - Energy Foundation Ghana -International organizations (UN)
Research agencies	- Support energy sector actor capacity - Strengthen professional development - Competitive research and client consulting	- The Energy Center, KNUST - Institute of Statistical, Social and Economic Research - Centre for Scientific and Industrial Research - Ghana Academy of Arts and Sciences
Unions- Energy sector and general	- Worker safety - Worker health - Worker income	- Industrial and Commercial Workers Union - Public Utility Workers Union - Public Service Workers Union
Professional organizations	- Professional development	- Ghana Institution of Engineers

References: (EC, 2006a; EC and MoE, 2012; Republic of Ghana, 2014; Appiah, 2015; Atarah, 2015; EOREE, 2015a, 2015b, 2015c) Adapted from von Wintrfeldt and Fasolo (2009) and van Beeck (2003).

5.4 Key parameters – Energy Demand and Supply Model

A set of key parameters was required as input for the energy demand and supply model in order to establish a scenario, which served as a socio-economic backdrop. The following section details these key parameters for the planning horizon. In order to have results that are comparable with SNEP the key parameters, when available, followed the values cited in the SNEP.

5.4.1 Population and households

The population in Ghana is forecast to grow to approximately 33.2 million by 2020 from 21.8 million in 2008. The largest share of this population resides in rural areas; however, the share of urban population grows from 40% to 48% by 2020. The population projection was established based on values cited in EC (2006d) as well as assumptions and calculations regarding the share of the PeriUrban population, which was not specifically assessed in the SNEP. This included the share that each population type represented of the total population as detailed in Section 4.2.2.2.

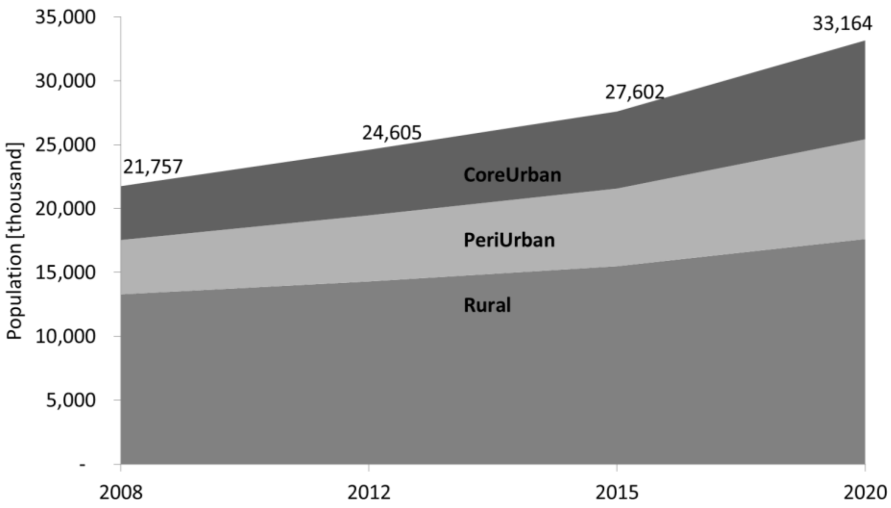

Figure 5-3 - Population Projection: Ghana 2008-2020

The household (HHS) sizes assumed were based on information from EC (2006d) and additional sources to establish the 3rd category of PeriUrban households. Assumptions regarding the household size were held constant for the planning horizon, due to lack of detailed information about their possible evolution.

The total number of households corresponding to each population type was forecast to grow from approximately 5.0 million to 7.7 million, see Figure 5-4.

Table 5-2 – Household size assumptions: Ghana 2008-2020

Household size [inhabitants/HHS]	2008	2012	2015	2020
CoreUrban	3.4	3.4	3.4	3.4
PeriUrban	5.5	5.5	5.5	5.5
Rural	4.4	4.4	4.4	4.4

References: (EC, 2006d; UN-Habitat, 2011)

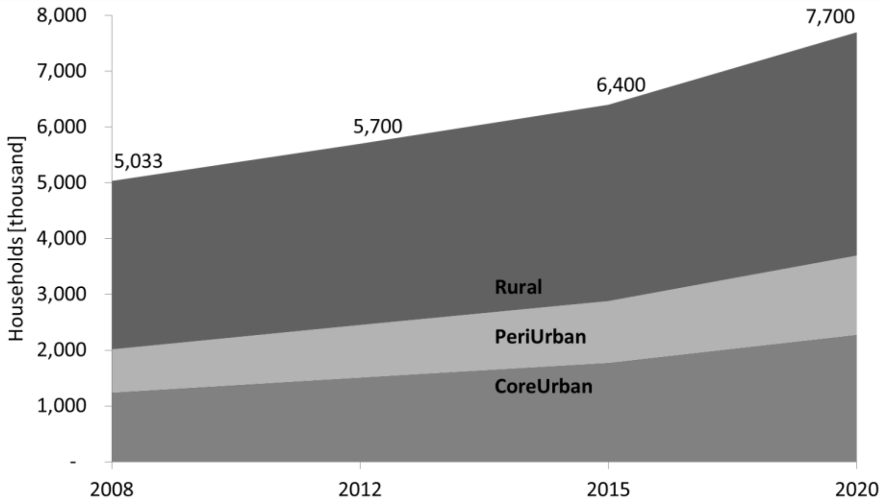

Figure 5-4 – Households Projection: Ghana 2008 – 2020

5.4.2 Economic

Economic growth in the SNEP was forecast for the period from the base year of 2008 to 2020 in three separate scenarios named: (1) *Business as Usual Economic Growth*, (2) *Moderately High Economic Growth*, and (3) *High Economic Growth*. These scenarios were based on those established in the GPRS I.

The current work follows the third scenario, *High Economic Growth*, cited in the SNEP which represented the scenario with the most detailed assumptions. In addition, the alternatives which were modeled and forecast within this scenario contained the most clearly detailed results, allowing for comparison. Finally, Ghana had already surpassed the forecasted GDP of this scenario for 2015 (World Bank, 2015a).

The GDP is forecast to grow from 19.5 billion in 2008 to 60 billion US $ in 2020. This corresponds to a growth in GDP per capita from approximately 896 to 1,809 US $ per capita in the same time horizon.

Table 5-3 – Main economic indicators: Ghana 2008 – 2020

Economic indicators	2008	2012	2015	2020
GDP [billion US $]	19.5	25.6	34.0	60.0
GDP/capita [billion US $ / capita]	896.3	1,040.4	1,231.8	1,809.2

References: (EC, 2006d), calculations

The GVA of the Service sector is forecast to take the largest share of productive sectors by 2020 growing from a share of 36 to 41 percent from 2008 to 2020. Growth in the Industry sector shows less growth in its total share than the Service sector. The Agriculture and Fishery sector shows contraction in the share. The shares in the total GVA are shown in Figure 5-5.

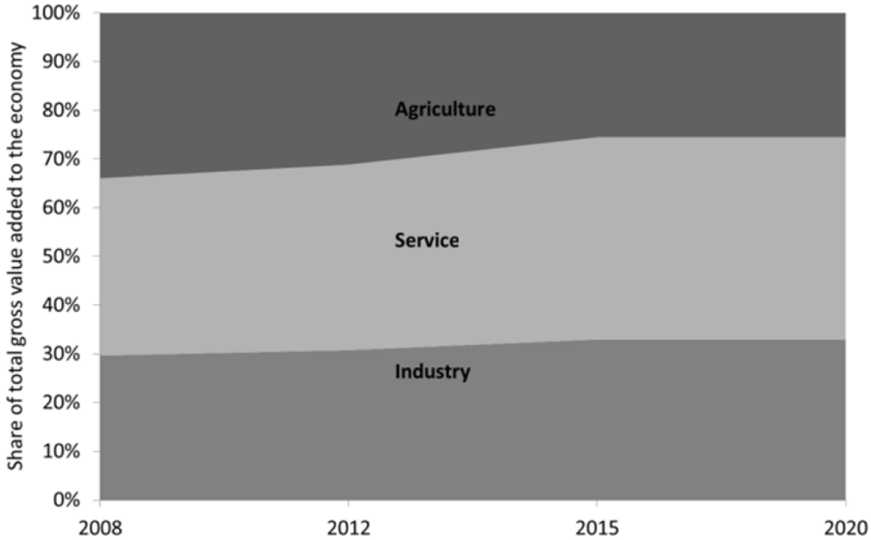

Figure 5-5 – Productive sector shares in GVA: Ghana 2008 – 2020 (EC, 2006d)

5.5 Access to electricity

Assumptions regarding the share of population that has access to FE carriers are both inputs which are fed to the national energy system model as well as to the quantifiable attribute corresponding to the objective to *Maximize access to modern energy* in Section 3.6.4.

The energy access levels assumed for the current work correspond to the Residential sector and the FE carriers considered for this sector. The energy access rate assumptions for the planning horizon are shown in Table 5-4, and described in the next paragraphs.

Here 100% of the population was assumed to have access to fuelwood for the planning horizon. While 100% of the population may not utilize this FE carrier for cooking and water heating, it was assumed that it was nonetheless accessible.

The access rate for charcoal was based on an energy use survey which reported 80% of urban households and 76% of rural households using charcoal in 2010 (EC, 2011a). In the absence of a specific data set for access, this rate of use was used as a placeholder. This value was assumed to remain constant for the planning horizon. This assumption was due to efforts to increase access to modern energy as opposed to traditional fuels (e.g. biomass based fuels) (EC and MoE, 2012).

Kerosene access rates were based on interactions with energy sector actors in Ghana as part of efforts to verify assumptions. CoreUrban populations were assumed to have 100% access, which was held constant for the planning horizon. Diminishing rates of access were assumed for PeriUrban and Rural populations.

LPG and electricity represent the FE carriers with the lowest levels of access, especially within rural populations. LPG rates of access were based on LPG use values for urban and rural populations reported by Edjekumhene (2011) for previous studies of rates in 2000 and 2010. A constant annual growth rate was calculated and applied for the planning horizon from these values. Electricity access rates were based on values reported for electrified communities in Ghana from Vanderpuye (2010), their respective populations, and assumptions on household sizes, see Table 5-2. A constant annual growth rate is assumed to reach 100% access by 2020 following the value reported in EC (2006a).

Table 5-4 – Energy access rate assumptions: Ghana 2008 – 2020 – Reference projection

Access rate [% of households]		Year			
FE carrier	Population type	2008	2012	2015	2020
Fuelwood	CoreUrban	100	100	100	100
	PeriUrban	100	100	100	100
	Rural	100	100	100	100
Charcoal		80	80	80	80
		80	80	80	80
		76	76	76	76
Kerosene		100	100	100	100
		90	90	90	90
		80	80	80	80
LPG		35	41	45	53
		20	24	27	33
		3	3	4	5
Electricity		86	90	94	100
		86	90	94	100
		55	70	81	100

References: (EC, 2006a)

The energy service portfolios and the access rate of households by population type are presented in Table 5-6.

Access to electricity, as discussed in the energy modeling Chapter 4, is achieved through three alternative methods. These consist of the national grid, minigrids and stand-alone systems. Access to electricity for CoreUrban and PeriUrban households is exclusively available through the national grid, as discussed previously.

Within the reference projection, the national grid is favored for efforts to increase access to electricity for Rural households. It is assumed that 80% of new Rural household access connections are to the national grid and the remaining 20% is split evenly between Minigrid and Standalone access. This is in line with current policies and efforts in Ghana and SSA which give preference to grid access (EC, 2006a; Rosnes and Vennemo, 2009). The share of households that receive access through each of these connection options is presented in Table 5-5.

Table 5-5 – Share of household electricity connections by type: Ghana reference projection

Share [% of new household connections]													
Electricity access connection type	Year												
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CoreUrban													
National Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
PeriUrban													
National Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
Rural													
National Grid	0	80	80	80	80	80	80	80	80	80	80	80	80
Minigrid	0	10	10	10	10	10	10	10	10	10	10	10	10
Standalone	0	10	10	10	10	10	10	10	10	10	10	10	10

Assumptions

For this work the households are assumed to have access to only one specific portfolio of FE carriers. For example, if a household has access to Firewood, Kerosene and LPG it is assumed to have access to the FW+Ker+LPG portfolio only, and this household cannot not have access to the FW+LPG or FW-only portfolios. The portfolios representing access to electricity are assumed to have access to fuelwood although they are not explicitly in the portfolio names. The assumptions for access to portfolios, presented in Table 5-6, are based on the original access rates to specific FE carriers as specified in Table 5-4 and additional assumptions.

Table 5-6 – Energy carrier portfolio access rate assumptions: Ghana reference projection

Access rate [% of households]		Year			
Energy carrier portfolio	Population type	2008	2012	2015	2020
Fuelwood (FW)- only	CoreUrban	0	0	0	0
	PeriUrban	1.1	0.7	0.4	0
	Rural	8.8	5.9	3.6	0
FW + Kerosene (Ker)		9.3	5.6	3.3	0
		10.3	6.5	3.9	0
		35.4	23.4	14.5	0
FW + LPG		0	0	0	0
		0.3	0.2	0.2	0
		0.2	0.2	0.1	0
FW + Ker + LPG		4.9	3.9	2.7	0
		2.6	2.1	1.5	0
		0.9	0.8	0.6	0
Electricity- Grid (Elec-G)		56.1	53.7	51.5	47.2
		68.5	68.5	68.3	67.4
		53.2	64.6	72.9	86.7
Elec-G + LPG		29.6	36.8	42.5	52.8
		17.2	22.0	25.8	32.6
		1.4	2.2	2.9	4.3
Electricity- MiniGrid (Elec-MG)		0	0	0	0
		0	0	0	0
		0	1.5	2.5	4.3
Elec-MG + LPG		0	0	0	0
		0	0	0	0
		0	0	0.1	0.2
Electricity- Standalone (Elec-STAL)		0	0	0	0
		0	0	0	0
		0	1.4	2.5	4.3
Elec-STAL + LPG		0	0	0	0
		0	0	0	0
		0	0	0.1	0.2
References: (EC, 2006a) assumptions					

5.6 Energy demand model – Ghana

Utilizing the national energy system model of Ghana detailed in Chapter 4, the FE demand in the base year of 2008 was characterized. After establishing FE demand for the base year, a “business as usual” reference projection of FE demand was constructed for the planning horizon. A description of the aggregate FE demand in the base year and for the planning horizon, within the Reference Projection, is presented here. This is followed by a detailed description of base year demand and FE demand along The Reference Projection within each sector.

The Residential sector represents the largest FE demand sector in the base year 2008 as shown in the disaggregation of FE demand by sector in Figure 5-6. Following the Residential sector, the Industry and Transport sectors represent the largest shares of FE demand. The Service and Agriculture sectors represented a relatively small proportion of the total FE demand in Ghana.

The Residential sector's large share of FE demand is primarily due to demand for fuelwood and charcoal, which were the predominant energy carriers for cooking and water heating, as discussed previously in the energy demand considerations of Section 4.5.

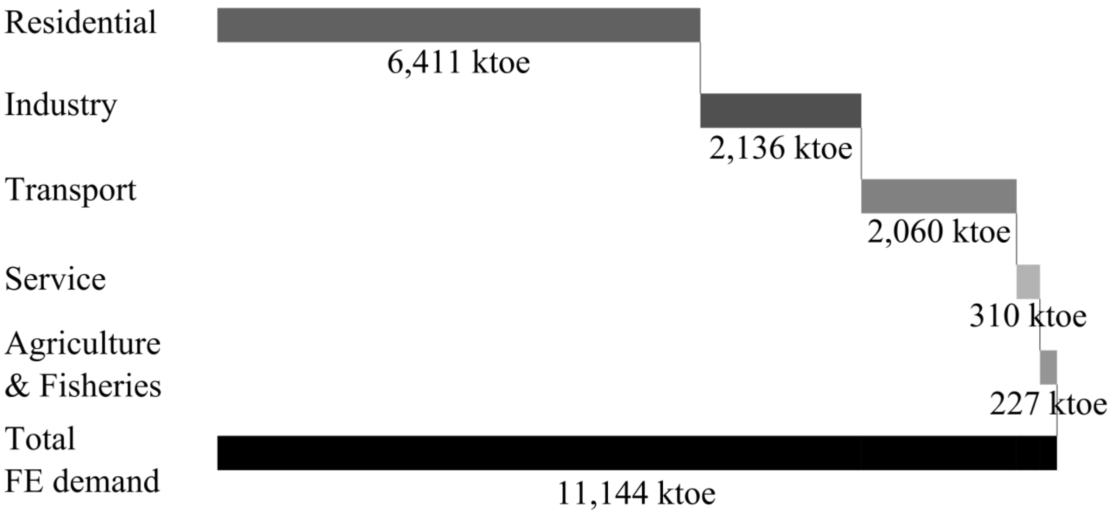

Figure 5-6 – Total FE demand disaggregated by sector: Ghana 2008

Table 5-7 presents the share that each FE carrier represents of total FE demand in 2008. The share of fuelwood in total FE demand is above 50% in the base year. In addition to fuelwood, charcoal represents over 10% of total FE demand. Petroleum based FE carriers for the Transport sector (e.g. diesel and gasoline) also represent significant shares of the total FE demand following fuelwood. Electricity represents just over 10% of total FE demand in the base year.

The total FE demand for the Reference Projection is shown in Figure 5-7. Total FE demand in the Reference Projection developed for Ghana more than doubled from 11,144 ktoe to 22,673 ktoe from 2008 to 2020. The Residential sector maintains the largest share of FE demand and is seen to represent a large share of the total growth in demand, as does the Industry sector. FE demand from the Agriculture and Service sectors remain relatively insignificant in total FE demand.

Table 5-7 - Share of total FE demand by FE carrier: Ghana 2008

FE Carriers	Share of total FE demand [%]
Fuelwood	52.3
Charcoal	12.9
Diesel	11.0
Electricity- Grid	10.0
Gasoline	6.7
LPG	2.2
RFO	1.7
Kerosene- Aviation	1.3
Gasoline- Premix	1.0
Kerosene- General	0.7
Direct Solar-Thermal	0.2
Electricity- MiniGrid	0.0
Electricity- Standalone	0.0

Calculations

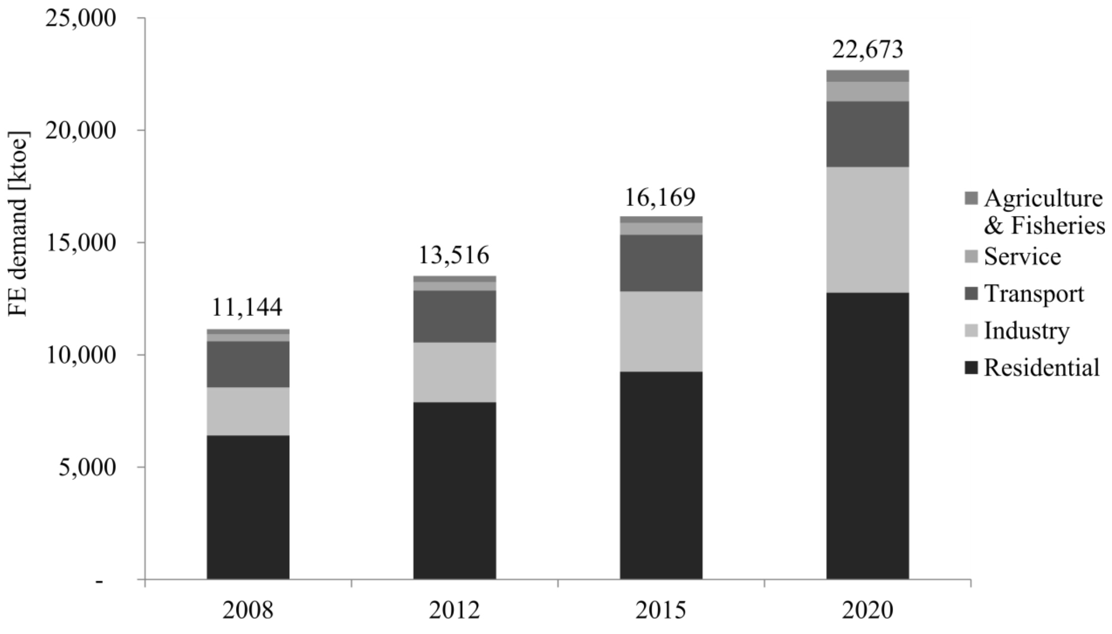

Figure 5-7 – FE demand projection – disaggregated by sector: Ghana reference projection

5.6.1 Residential sector demand

The total FE demand of the Residential sector is composed of the demand from the CoreUrban, PeriUrban and Rural subsectors. The total FE demand attributable to each of the subsectors is shown in Figure 5-8. Here the Rural sector is seen to represents 71% of the FE demand. This overwhelming share of the demand reflects the use of fuelwood for cooking and water heating.

As presented in Section 4.5, the Residential sector represents the largest share of FE demand. Cooking and water heating together represent 100% of the fuelwood demand.

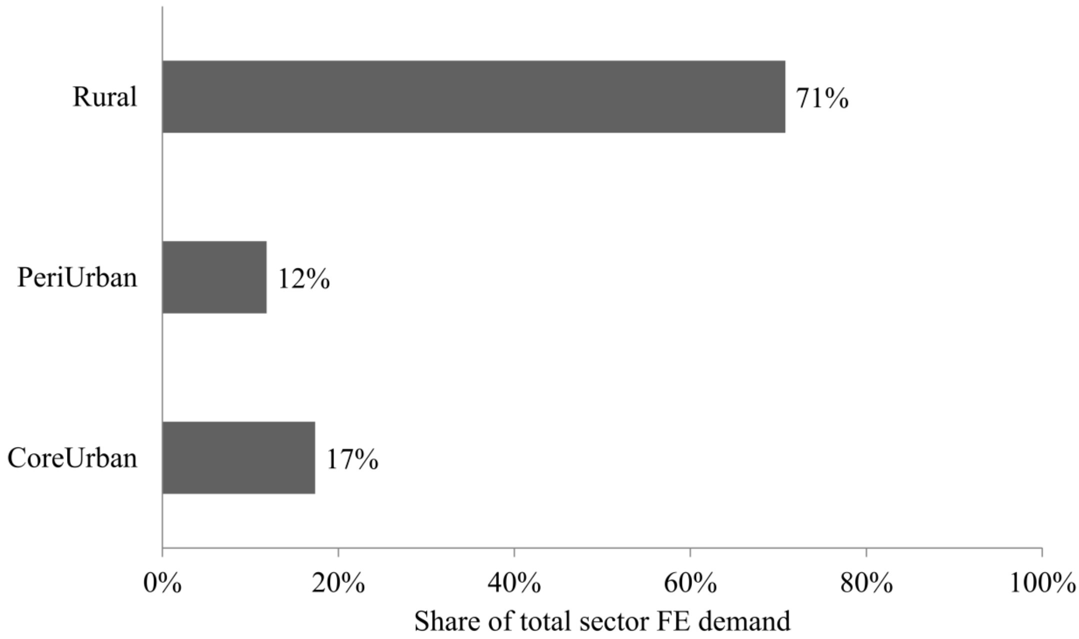

Figure 5-8 - Residential subsectors share of total FE demand - Ghana 2008

The residential FE demand originates from demand in the sector for ten FE services. These FE services are (1) cooking, (2) lighting, (3) water heating, (4) refrigeration, (5) freezing, (6) audiovisual, (7) information technology, (8) Air-conditioning, (9) clothes washing, and (10) dish washing. The estimated share of total FE demand in the Residential sector by service is seen in Table 5-8. Cooking and water heating represent 67% and 23% of the demand, due to the predominant demand for fuelwood as a FE carrier for these FE services. The estimated efficiency for cooking and water heating with a traditional three-stone fuelwood stove assembly is 15.5% as shown in Table 5-10.

The FE demand model for the Residential sector was detailed in Section 4.6.2. To complete this section for the specific case study of Ghana, additional assumptions were necessary regarding the end-use technologies used at the household level. The first component in making the model specific to the context of Ghana was assumptions regarding the household ownership of appliances in Ghana. In complement to the first component are the end-use technologies used at the household level and the assumed mix of FE technologies used to construct a representative composite appliance for each FE service and carrier combination. This appliance is modeled as a weighted average mix of technologies and corresponding efficiencies.

Table 5-8 – Residential - FE services share of total sector FE demand – Ghana 2008

FE Service	Share of total sector FE demand [%]
Cooking	66.9
Water heating	22.8
Lighting	3.6
Refrigeration	1.9
Audiovisual	1.9
Freezing	0.9
Information Technology	0.5
Air conditioning	0.5
Clothes washing	0.5
Dish washing	0.5

Calculations

The household ownership and saturation levels for the appliances are shown in Table 5-9. These values were assumed based on information available from EC (2006a). The levels for Electricity – Minigrid and Standalone are not represented in this table as they were assumed to be equal to the values assumed for the Electricity-Grid in the base year.

End-use conversion technologies convert FE carriers into usable forms that allow for FE service demand to be met. There are many end-use conversion technologies and the specific technologies used within a population can vary for different populations. The conversion technologies and the FE carriers are not completely interchangeable in that FE carriers can only make available certain FE services through the use of specific end-use technologies. Electricity, for example, can provide for various FE services such as cooking, lighting and space cooling, while fuelwood is limited to cooking and heating, and cannot provide for (modern) lighting and space cooling demands. The end-use technologies are specific to the FE carrier as the cook stove used with electricity is not interchangeable with a fuelwood cook stove.

Base year assumptions for technology share in the end-use mix and efficiencies for the Residential and Service sectors are based, where possible, on reported values from a technology catalog from EC (2004) which was developed to support the SNEP (2006).

The values used for the technologies in the end-use mixes are conservative for the base year and the planning horizon. This is due to the fact that much of the technologies or appliances in use in Ghana, as in many developing countries, are imported or recirculated as second hand products. These often originate from more developed regions such as the United States and Europe. When regulations are not in place in the country of destination, these products may not be representative of the current available market in much of the more developed world. These products are often for sale in informal market places in the destination country and not officially regulated in terms of safety or efficiency. This implies that technologies may be older technologies and often less efficient then modern available technologies. While this is the case, products are also available, which represent modern technologies available in much of the developed world. These are also imported and available mostly in more regulated official market places.

Table 5-9 - Residential - Household ownership of appliances by service & carrier: Ghana 2008

Household ownership [appliances/household]				
FE service – carrier combination	CoreUrban	PeriUrban	Rural	Saturation level
Cooking – Biomass	0.203	0.843	0.843	1.000
Cooking – Charcoal	0.577	0.142	0.142	1.000
Cooking – LPG	0.220	0.015	0.015	1.000
Cooking – Electricity- Grid	0.000	0.000	0.000	1.000
Lighting – Kerosene	0.191	0.513	0.820	1.000
Lighting – Electricity- Grid	0.809	0.487	0.180	5.000
Water heating – Biomass	0.203	0.843	0.843	1.000
Water heating – Charcoal	0.577	0.142	0.142	1.000
Water heating – LPG	0.220	0.015	0.015	1.000
Water heating – Electricity- Grid	0.038	0.011	0.011	1.000
Refrigeration – Electricity- Grid	0.493	0.325	0.072	1.000
Freezing – Electricity	0.137	0.071	0.020	1.000
Audiovisual – Electricity	0.729	0.479	0.159	3.000
Info. Tech. – Electricity- Grid	0.066	0.028	0.006	3.000
Air conditioning – Electricity- Grid	0.018	0.001	0.001	2.000
Clothes washing – Electricity- Grid	0.019	0.002	0.001	1.000
Dish washing – Electricity- Grid	0.019	0.002	0.001	1.000

(EC, 2006a), calculations

Cooking in the Residential sector consists primarily of fuelwood, charcoal and LPG stoves. The use of electric stoves for cooking is not ordinary and demand for electricity in cooking was described as insignificant (EC, 2006d).

The residential cooking technology mix is shown in Table 5-10. For fuelwood cooking stoves a shift to improved cookstoves was assumed of 1 percentage points (pp) annually from both 3-

stone and mud stoves. The sawdust cookstove was reported to not be in use. For charcoal cookstoves a 1 pp a year shift from traditional to improved cookstoves was assumed. Ceramic "Jiko" cookstoves were reported to not be common and assumed to be zero for the planning horizon. LPG tabletop stoves and combined cooker & ovens were assumed to have the same efficiency but a gradual shift to the later of the two is assumed for the planning horizon (EC, 2004).

Table 5-10 – Residential - cooking technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency	2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35	31	28	23
Improved fuelwood stove	32.5	5	13	19	29
Traditional mud stove	17.5	60	56	53	48
Sawdust stove	26.2	0	0	0	0
Charcoal					
Traditional stove -*Coal pot*	21.0	75	71	68	63
Improved stove	34.5	25	29	32	37
Ceramic stove - *Jiko*	45.2	0	0	0	0
LPG					
Tabletop stove	57.5	70	66	63	58
LPG Stove-cooker/oven	57.5	30	34	37	42
LPG Metal cabinet oven	57.5	0	0	0	0

References: (EC, 2004, 2006d)

Residential sector lighting, Table 5-11, consists of electric lamps as well as kerosene lanterns (EC, 2006d). The efficacy used here for lighting technologies is a measure of the lumens per Watt, where lumen is the measure of the visible light emitted by a source. Residential households use kerosene lamps of which the most common technology is a traditional wick lantern. Incandescent lamps as well as fluorescent T12 lamps were common residential lamp types in the base year (Constantine et al., 1999).

In 2003 import taxes on CFLs were removed, following which in 2007 a program to exchange CFLs for incandescent was conducted. Lamp efficiency standards have been enacted to ensure a minimum efficacy for lighting technologies effectively removing incandescent lamps from the marketplace (EC, 2009b, 2015a). The share of CFLs was expected to grow to 34% of electric lighting technologies, and LED lamps were expected to enter into the mix by 2020.

The shares of Kerosene lighting technologies were assumed to remain constant within the planning horizon as no evidence of efforts to shift from the less efficacious wick lantern to the more efficacious pressure lamp was found in the literature. For electric lighting, following the lamp efficiency efforts described above, incandescent lamps were assumed to reach a 0% share of technologies by 2020 with a constant annual rate of decline of 25% (of share value) annually. CFL lamps were assumed to replace the decreasing share of incandescent lamps. A shift was assumed from T12 fluorescent magnetic ballast lamps, 2 pp annually, to T8 lamps until 2020. The share of T5 lamps increases 1 pp annually from 2015 to 2020. A small share of mix was assumed to be made of LED lamps by 2020.

Table 5-11 – Residential - lighting technologies end-use mix: Ghana reference projection

Technology	Efficacy [Lumens/Watt]	Share in end-use mix [%]			
		2008	2012	2015	2020
Kerosene - [lumens/ Liter]					
Kerosene wick lantern	0.13	70	70	70	70
Kerosene pressure lamp	0.99	30	30	30	30
Electricity - [lumens/Watt]					
Incandescent lamp (100 Watt)	12.00	34	11	5	0
Fluorescent F40T12 4’ 34W + magnetic ballast system	80.00	65	57	51	36
Fluorescent F32T8 4’ 32W + electronic ballast system	90.00	0	8	14	24
Fluorescent F28T5 4’ 28W + electronic ballast system	100.00	0	0	0	5
CFL	67.00	1	24	30	34
LED lamp	94.00	0	0	0	1
LED tube lamp	100.00	0	0	0	0

References: (Constantine et al., 1999; EC, 2004; Schwarz et al., 2005; EC, 2006d; LRC, 2015)

Water heating was not a FE service considered explicitly in the SNEP from the EC (EC, 2006d). The reasons for this may lie in historical trends in household FE service demand due to affluence, geography and climate (IEA, 2006b). For the current work it was considered explicitly, and despite the warm climate of Ghana it was assumed to factor into Residential sector demand and become a more significant share of total FE demand in the sector as households become more affluent.

Water heating technologies were considered for fuelwood, charcoal, LPG and electricity, Table 5-12. Fuelwood, charcoal and LPG water heating technologies were assumed to be identical to cooking technologies as households share the same technology for both services. LPG tank heaters were not included in the end-use mix as they were not present in the country as gas is purchased in cylinders and there is no gas network infrastructure.

Electric water heaters used in Ghana were found by EC (2004) to include emersion heaters, electric kettles, and instant flow water heaters. The SNEP in 2006 recommended that the government adopt policies to promote solar thermal water heaters (EC, 2006d). As these instant water heating technologies require energy use at peak hours of the day when populations are preparing to leave for work or alternatively when they arrive at the end of the day, there would be little room for DSM efforts. An assumption was made that with increased affluence storage-tank type hot water heaters may enter into the market.

Here, an efficiency over 100% results from the assumption that there is a contribution from direct solar thermal renewable energy, which is considered a “free” contribution of FE, in addition to commercial FE carriers such as electricity and gas. An example would be an electric hot water heater with an efficiency of 90% which has a 30% contribution from solar thermal energy and has a resulting efficiency of 0.9/0.7 or 129% (CUSCST, 2011).

Shares in the end-use mix of water heating of fuelwood and charcoal technologies for the planning horizon (Table 5-12) were assumed to be identical to cooking technologies shares, as it was assumed the same technology would be used in the household. It was assumed that tabletop stoves remain the only LPG water heating technology as LPG is available only in tanks. Emersion style and kettle type electric water heaters were assumed to be the most common due to descriptions in the EC (2004). A 1 pp annual decline in the end-use mix share was assumed for both of these technologies. Instant flow water heaters were assumed to have a constant share due to increased use of insulated tank water heaters. A 1% growth was assumed in the share of inefficient Class G insulated tank water heaters, 0.4% increase in moderately efficient Class C heaters, and a 0.5 pp annual increase in the share of efficient Class A water heaters. Solar water heaters were assumed to reach 8% share of the end-use mix due to promotional efforts at the government level (EC, 2006e).

Refrigeration and freezing were separated in the current work, and the technology mixes are presented in Table 5-13 and 5-14. A large share of the refrigeration technologies in Ghana are imported secondhand appliances with relatively low energy efficiency levels (EC, 2004). Ghana has developed refrigerator energy efficiency guide labels which have also been proposed to be developed into a standard as part of a policy to limit imported used appliances (Ben Hagan, 2007; Van Buskirk et al., 2007). The efficiency guide is based on a 5-star rating system, with labels placed on new technologies for sale. In addition, a refrigerator exchange and rebate program was started by the EC and the UNDP (MoE, 2009b; EC, 2015b). Freezing technologies were assumed to be horizontal chest style freezers. Assumptions for freezing were based on those that were identified for refrigeration as the standard and labeling programs were recommended to be passed on to freezing and other appliances by the EC (2006d).

A shift was assumed to occur over the planning horizon away from inefficient unlabeled refrigerators at a rate of 2 pp annually in the share of the end-use mix. A shift towards labeled refrigerators was assumed of 1.5 pp, 0.3 pp, and 0.2 pp annually for 1 Star, 2 Star and 4 Star appliances respectively.

A shift was assumed to occur over the planning horizon away from inefficient unlabeled freezers at a rate of a 2 pp annually. The share of 1 Star, 2 Star and 4 Star appliances was assumed to increase by 1.5 pp, 0.3 pp, and 0.2 pp per year respectively.

Table 5-12 – Residential - water heating technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%]			
		2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	31.0	28.0	23.0
Improved fuelwood stove	32.5	5.0	13.0	19.0	29.0
Traditional mud stove	17.5	60.0	56.0	53.0	48.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	75.0	71.0	68.0	63.0
Improved stove	34.5	25.0	29.0	32.0	37.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	100.0	100.0	100.0	100.0
Insulated storage-tank heater	92.0	0.0	0.0	0.0	0.0
Electricity- [Energy Efficiency Index]					
Emersion heater - 1500W	13.0	36.5	32.5	29.5	24.5
Kettle-2000W	13.0	36.5	32.5	29.5	24.5
Instant flow heater -4000W	97.0	5.0	5.0	5.0	5.0
Solar heater - 175liter storage tank	188.1	2.0	4.0	5.5	8.0
Insulated tank heater - Class G	26.0	20.0	24.0	27.0	32.0
Insulated tank heater - Class F	28.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class E	32.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class D	35.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class C	43.5	0.0	1.6	2.8	4.8
Insulated tank heater - Class B	62.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A	95.0	0.0	0.4	0.7	1.2
Insulated tank heater - Class A+	32.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A++	69.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class A+++	188.1	0.0	0.0	0.0	0.0

References: (EC, 2004, 2006d; European Commission, 2013; DOE, 2015; EPA, 2015) assumptions

Table 5-13 – Residential - refrigeration technologies end-use mix: Ghana reference projection

Technology	Efficiency [Energy Efficiency Index- 100 is least efficient]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Refrigerator[1] prior to regulation	100.0	80.0	72.0	66	56
1 Star[2] refrigerator	95.0	10.0	16.0	20.5	28
2 Star refrigerator	82.5	10.0	11.2	12.1	13.6
3 Star refrigerator	65.0	0.0	0.0	0.0	0.0
4 Star refrigerator	48.5	0.0	0.8	1.4	2.4
5 Star refrigerator	41.0	0.0	0.0	0.0	0.0

1. All are assumed to be combined Refrigerator +Freezer
2. Star rating refers to the energy efficiency standards and labeling regulations of Ghana (MoE, 2009b).
References: (EC, 2004, 2006d; MoE, 2009b)

Table 5-14 - Residential - freezing technologies end-use mix: Ghana reference projection

Technology	Efficiency [Energy Efficiency Index- 100 is least efficient]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Freezer Prior to regulation	100.0	80.0	72.0	66	56
1 Star[1] rated Freezer	95.0	10.0	16.0	20.5	28
2 Star rated Freezer	82.5	10.0	11.2	12.1	13.6
3 Star rated Freezer	65.0	0.0	0.0	0.0	0.0
4 Star rated Freezer	48.5	0.0	0.8	1.4	2.4
5 Star rated Freezer	41.0	0.0	0.0	0.0	0.0

1. Star rating refers to the energy efficiency standards and labeling regulations of Ghana (MoE, 2009b)

References: (EC, 2004, 2006d; MoE, 2009b)

Air-conditioning (AC) technologies in the Residential sector, as presented in Table 5-15, are uncommon in all household population types. It was assumed that the majority of the appliances were imported secondhand technologies and were either split system or window mount units. The Energy Efficiency Standards and Labeling Regulation of 2005 required the labeling of all imported and sold AC units in Ghana and set a minimum standard for energy efficiency for sale in the country. It was assumed that by 2020 these higher efficiency AC units would be present in the technology mix (EC, 2015a).

For the planning horizon, a 2 pp a year shift away from low EER AC units to AC units that are minimum EER or above was assumed. The shares in the end-use mix of minimum, high and highest EER AC units were assumed to increase at 1.5 pp, 0.4 pp and 0.1 pp annually.

Table 5-15 – Residential – air-conditioning technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Low EER[1] AC	2.25	90.0	82.0	76.0	66.0
Minimum EER AC	2.80	10.0	16.0	20.5	28
High EER AC	3.50	0.0	1.6	2.8	4.8
Highest EER AC	4.10	0.0	0.4	0.7	1.2

1. All AC units are assumed non ducted of various sizes

References: (Constantine et al., 1999; EC, 2004, 2006d; Hierzinger and Krivošík, 2012; EC, 2015a)

Ownership levels of clothes washing technologies are low within all population types, as shown in the household ownership values in Table 5-9. The representative end-use mix for Clothes washing technologies is shown in Table 5-16. It was assumed that the majority of appliances were used, imported secondhand, technologies, and that they represented less efficient technologies following the European classification system. There are currently no energy efficiency labeling or standards programs in Ghana and it was assumed there was an insignificant shift in the mix to more efficient technologies.

A shift in the share of the end-use mix of clothes washing technologies was assumed by 2012 to reach 90% and 10% Class D and more efficient Class C appliances respectively. Class B appliances are assumed to reach 10% of the share of the end-use mix by 2015 and the end-use mix was assumed to remain constant for the planning horizon.

It should be noted here that due to the climate and customs drying is done outdoors utilizing direct solar thermal heat. Electric clothes drying technologies were not used in the Residential sector.

Table 5-16 – Residential - clothes washing technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Class D appliance	87.0	100.0	90.0	80.0	80.0
Class C appliance	82.0	0.0	10.0	10.0	10.0
Class B appliance	72.5	0.0	0.0	10.0	10.0
Class A appliance	63.5	0.0	0.0	0.0	0.0
Class A+ appliance	55.5	0.0	0.0	0.0	0.0
Class A++ appliance	49.0	0.0	0.0	0.0	0.0

References: (EC, 2006d; European Commission, 2010a)

Dish washing technologies are not common in the Residential sector for any population type, Table 5-9. The representative end-use mix for dish washing technologies is shown in Table 5-17. The technologies, similar to clothes washing technologies were assumed to be imported second-hand relatively inefficient appliances.

With no appliance standard or labeling program in Ghana it was assumed that a small shift would occur to more efficient technologies by 2020.The dish washing technologies end-use mix was assumed by 2012 to reach 90% and 10% Class D and more efficient Class C appliances respectively. Class B appliances were assumed to reach 10% of the share of the end-use mix by 2015 and end-use mix was assumed to remain constant for the planning horizon.

A mix of standard audiovisual technologies representing televisions available on the market was used, Table 5-18 (CEC, 2009). The EC (2004) reported that CRT type televisions were the primary technology type, however it was assumed that additional technologies would enter into the mix during the planning horizon.

The CRT television technologies remain dominant in the end-use mix for the planning horizon. A large share of televisions and appliances in Ghana are imported secondhand appliances (EC, 2004). New appliances can be purchased in commercial stores, however used and imported appliances as well as new appliances are for sale in less formal market places. A small shift of 1 pp a year away from CRT technologies was assumed annually from 2008 to 2020. A 0.5 pp a year increase in the share of the end-use mix was assumed for both Plasma and LCD technologies.

Table 5-17 – Residential - dish washing technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Class D appliance	91.0	100.0	90.0	80.0	80.0
Class C appliance	85.0	0.0	10.0	10.0	10.0
Class B appliance	75.5	0.0	0.0	10.0	10.0
Class A appliance	67.0	0.0	0.0	0.0	0.0
Class A+ appliance	59.5	0.0	0.0	0.0	0.0
Class A++ appliance	53.0	0.0	0.0	0.0	0.0

References: (de Bruyn and Opschoor, 1997; EC, 2006d; FSEC, 2008; European Commission, 2010b)

Table 5-18 – Residential - audiovisual technologies end-use mix: Ghana reference projection

Technology	Power rating [Watts]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
CRT television	101	90.0	86.0	83.0	78.0
Plasma	361	5.0	7.0	8.5	11.0
LCD	144	5.0	7.0	8.5	11.0
LED LCD	108	0.0	0.0	0.0	0.0
OLED	72	0.0	0.0	0.0	0.0

References: (EC, 2004; CEC, 2009)

Information technologies consisted of computers in the current work and it was assumed these consist of desktop computers and laptops, Table 5-19. By the end of the planning horizon desktop computers represented a smaller share of the mix.

Desktop computers were assumed to be the dominant technology in the end-use mix in the base year with a 90% share. Laptop computers were assumed to have the largest share in the end-use mix by 2020 with 70%.

Table 5-19 – Residential - information technologies end-use mix: Ghana reference projection

Technology	Power rating [Watts]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Desktop computer	150	90.0	70.0	50.0	30.0
Laptop computer	20	10.0	30.0	50.0	70.0

References: (EC, 2004; EFG, 2013)

The reference projection for the Residential sector, Figure 5-9, forecasted the FE demand for the sector in 2020 to reach a level approximately twice that seen in 2008. This is reflective of the growth in households of all population types in the planning horizon. The increasing rate of end-use appliance ownership also contributes to increased demand for all FE carriers. The Residential sector continues to represent a large share of FE demand for fuelwood and charcoal, which contribute a large share of this demand, as shown in the national energy flow presented at the end of the current chapter in Figure 5-21.

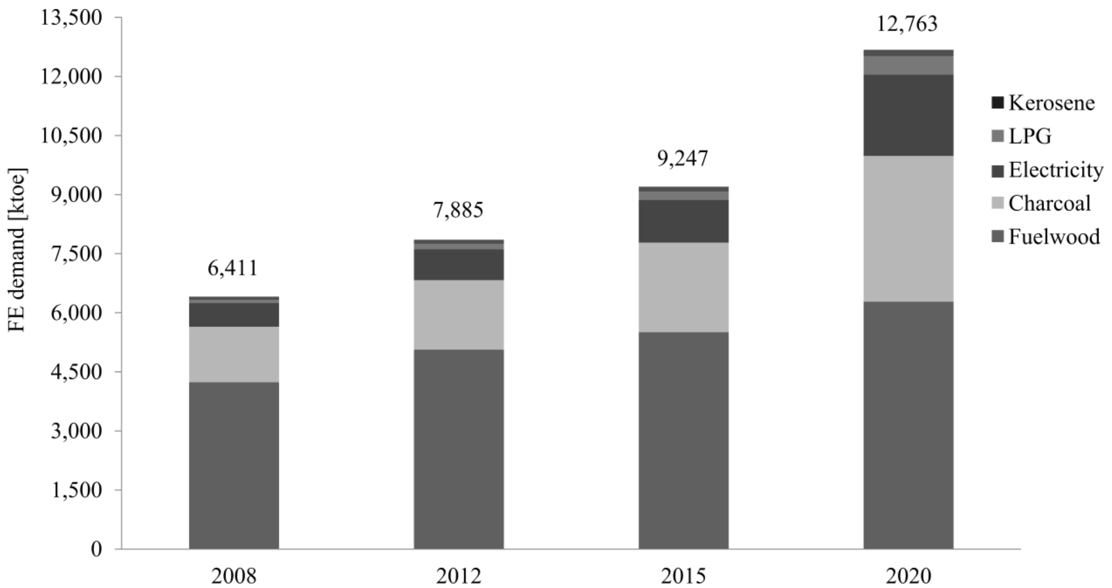

Figure 5-9 – Residential sector FE demand reference projection: Ghana reference projection

5.6.2 Service sector demand

The Service sector in Ghana was modeled as consisting of ten FE services which were reflective of those identified in the Residential sector. The FE services are (1) cooking, (2) lighting, (3) water heating, (4) refrigeration, (5) freezing, (6) audiovisual, (7) information technology, (8) Air-conditioning, (9) clothes washing, and (10) dish washing.

The Service sector in Ghana comprises a diverse mix of activities. These consist of both formal service offerings for tourism, offices, stores, health, education, restaurants and other services. It also consists of a diverse set of informal sector activities reflective of the formal service offerings (EC, 2006e).

The shares in total FE demand that each of these services represented in the base year of 2008 are shown in Table 5-20. Similar to the Residential sector, the FE services for cooking and water heating were principally met through fuelwood demand and resulted in the relatively large shares, 50.0% and 9.7% respectively, for these services, based on the assumptions made previously in Section 5.6.2. Also, the Service sector lighting represented the second largest share of total FE demand, 22.5%.

Table 5-20 – Service - FE services share of total sector FE demand: Ghana 2008

FE Service	Share of total sector FE demand [%]
Cooking	49.9
Lighting	22.5
Water heating	9.7
Refrigeration	4.2
Freezing	4.2
Air conditioning	4.2
Information Technology	3.3
Audiovisual	1.2
Clothes washing	0.4
Dish washing	0.4

Calculations

The FE demand model for the Service sector was detailed in Section 4.6.3. FE demand was forecast based on the EI [ktoe/GVA] of the Service sector for each FE service and carrier combination. The end-use technologies were represented by a Ghana specific representative composite appliance for each FE services and carrier combination. This appliance was modeled, as a mix of technologies and corresponding efficiencies through a weighted sum.

The end-use technologies considered were reflective of those considered in the Residential sector. This was due to the similarity in the FE services between the two sectors as well as the fact that the informal Service sector activities are often conducted at the household level or with similar technologies.

Cooking in the Service sector, as in the Residential sector, consists of fuelwood, charcoal and LPG technologies as presented in Table 5-21. Additional technologies were included in the mix that were used in commercial applications (EC, 2004). A slight increase in the share of efficient technologies such as improved fuelwood stoves was assumed along the planning horizon.

The 3-stone stove and commercial metal stove were assumed to be the most common cooking technologies in the base year and represented the largest shares in the end-use technology mix (EC, 2004). A 1 pp annual decrease of the share in the end-use mix was assumed for the 3-stone stove. This was assumed to represent a shift to improved cook stoves and commercial metal stoves. A 1 pp annual decrease was assumed for the traditional mud stove share in the end-use mix. The traditional bread oven share was not assumed to change in the planning horizon.

Table 5-21 - Service - cooking technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	31.0	28.0	23.0
Improved fuelwood stove	32.5	5.0	9.0	12.0	17.0
Traditional mud stove	17.5	20.0	16.0	13.0	8.0
Commercial metal stove	29.5	30.0	34.0	37.0	42.0
Traditional bread oven	29.5	10.0	10.0	10.0	10.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	50.0	46.0	43.0	38.0
Improved stove	34.5	20.0	24.0	27.0	32.0
Charcoal oven	21.0	22.5	22.5	22.5	22.5
Fish smoker	21.0	7.5	7.5	7.5	7.5
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	30.0	26.0	23.0	18.0
Stove-cooker/oven	57.5	50.0	54.0	57.0	62.0
Metal cabinet oven	57.5	20.0	20.0	20.0	20.0

References: (EC, 2004, 2006d)

Lighting in the Service sector consisted of kerosene and electricity lamps as LPG lanterns are not represented in the sector (EC, 2006d). Beyond the absence of LPG technologies, the mix was reflective of the lighting mix from the Residential sector as shown in Table 5-22.

The water heating end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, see Section 5.6.1, in the absence of more detailed data.

Water heating in the Service sector consists primarily of heating water for bathing in private bath houses, which use various FE carriers (namely fuelwood and charcoal) for heating (King et al., 2012). Water heating in the Service sector represented a less significant demand than it did in the Residential sector, however it is present in Ghana and the technology mix assumed consists of fuelwood, charcoal, LPG and electricity based appliances as depicted in

Table 5-23. The heating technologies for fuelwood and charcoal were identical to those used for cooking, as it was assumed the same technology would be used for either. LPG water heaters for the Service sector were assumed to include a share of insulated storage water heaters that would be used in hotels. Electric water heaters were identical to those assumed in the Residential sector. A slight shift toward efficient appliances was assumed during the planning horizon.

Table 5-22 - Service - lighting technologies end-use mix: Ghana reference projection

Technology	Efficacy [lumens/Watt]	Share in end-use mix [%] 2008	2012	2015	2020
Kerosene - [lumens/ Liter]					
Kerosene wick lantern	0.13	70	70	70	70
Kerosene pressure lamp	0.99	30	30	30	30
Electricity - [lumens/Watt]					
Incandescent lamp (100 Watt)	12.0	34.0	11.0	5.0	0.0
Fluorescent F40T12 4’ 34W + magnetic ballast system	80.0	65.0	57.0	51.0	36.0
Fluorescent F32T8 4’ 32W + electronic ballast system	90.0	0.0	8.0	14.0	24.0
Fluorescent F28T5 4’ 28W + electronic ballast system	100.0	0.0	0.0	0.0	5.0
CFL	67.0	1.0	24.0	30.0	34.0
LED lamp	94.0	0.0	0.0	0.0	1.0
LED tube lamp	100.0	0.0	0.0	0.0	0.0

References: (Constantine et al., 1999; EC, 2004; Schwarz et al., 2005; EC, 2006d; LRC, 2015)

The water heating end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1, in the absence of more detailed data.

The refrigeration and freezing technologies assumed for the Service sector were the same as those within the Residential sector and are shown in Table 5-24 and Table 5-25. The refrigeration standards and labeling program and rebate program discussed in the Residential demand section were assumed to influence the mix of technologies (Ben Hagan, 2007; MoE, 2009b). Additionally, a refrigerator exchange and rebate program was started by the EC and the UNDP. Freezing technologies were assumed to be horizontal chest style freezers. Assumptions for freezing were based on those that were identified for refrigeration.

The refrigeration and freezing end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-23 – Service - water heating technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	31.0	28.0	23.0
Improved fuelwood stove	32.5	5.0	9.0	12.0	17.0
Traditional mud stove	17.5	20.0	16.0	13.0	8.0
Commercial metal stove	29.5	40.0	44.0	47.0	52.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove - *Coal pot*	21.0	75.0	71.0	68.0	63.0
Improved stove	34.5	25.0	29.0	32.0	37.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	75.0	71.0	68.0	63.0
Insulated storage-tank heater	92.0	25.0	29.0	32.0	37.0
Electricity					
Emersion heater - 1500W	13.0	36.5	32.5	29.5	24.5
Kettle-2000W	13.0	36.5	32.5	29.5	24.5
Instant flow heater -4000W	97.0	5.0	5.0	5.0	5.0
Solar heater - 175liter storage tank	188.1	2.0	4.0	5.5	0.08
Insulated tank heater - Class G	26.0	20.0	24.0	27.0	32.0
Insulated tank heater - Class F	28.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class E	32.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class D	35.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class C	43.5	0.0	1.6	28	4.8
Insulated tank heater - Class B	62.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A	95.0	0.0	0.4	0.7	1.2
Insulated tank heater - Class A+	133.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class A++	169.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class A+++	188.1	0.0	0.0	0.0	0.0

References: (EC, 2004, 2006d; European Commission, 2013; DOE, 2015; EPA, 2015) assumptions

Table 5-24 – Service - refrigeration technologies end-use mix: Ghana reference projection

Technology	Efficiency [Energy Efficiency Index- 100 is least efficient]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Refrigerator[1] prior to regulation	100.0	80.0	72.0	66.0	56.0
1 Star[2] refrigerator	95.0	10.0	16.0	20.5	28.0
2 Star refrigerator	82.5	10.0	11.2	12.1	13.6
3 Star refrigerator	65.0	0.0	0.0	0.0	0.0
4 Star refrigerator	48.5	0.0	0.8	1.4	2.4
5 Star refrigerator	41.0	0.0	0.0	0.0	0.0

1. All are assumed to be combined Refrigerator +Freezer
2. Star rating refers to the energy efficiency standards and labeling regulations of Ghana (MoE, 2009b).
References: (EC, 2004, 2006d; MoE, 2009b)

Table 5-25 – Service - freezing technologies end-use mix: Ghana reference projection

Technology	Efficiency [Energy Efficiency Index]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Freezer prior to regulation	100.0	80.0	72.0	66.0	56.0
1 Star[1] rated Freezer	95.0	10.0	16.0	20.5	28.0
2 Star rated Freezer	82.5	10.0	11.2	12.1	13.6
3 Star rated Freezer	65.0	0.0	0.0	0.0	0.0
4 Star rated Freezer	48.5	0.0	0.8	1.4	2.4
5 Star rated Freezer	41.0	0.0	0.0	0.0	0.0

1. Star rating refers to the energy efficiency standards and labeling regulations of Ghana (MoE, 2009b)
References: (EC, 2004, 2006d; MoE, 2009b)

The air-conditioning end-use technology mix is shown in Table 5-26. Air-conditioning is common in hotels and guesthouses as well as office buildings. AC units are also common in stores in urban areas as well as information technology centers. The Energy Efficiency Standards and Labeling Regulation of 2005 set a minimum standard for energy efficiency for sale in the country and it was assumed that by 2020 a small percentage of these higher efficiency AC units would be present in the technology mix (EC, 2015a).

The AC end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-26 – Service - air-conditioning technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Low EER[1] AC	2.25	90.0	82.0	76.0	66.0
Minimum EER AC	2.80	10.0	16.0	20.5	28.0
High EER AC	3.50	0.0	16.0	2.8	4.8
Highest EER AC	4.10	0.0	0.4	0.7	1.2

1. All AC units are assumed non ducted of various sizes
References: (Constantine et al., 1999; EC, 2004, 2006d; Hierzinger and Krivošík, 2012; EC, 2015a)

Clothes washing in the Service sector consists of commercial laundry mats in urban areas as well as hotels and guesthouses. The technology mix assumed is shown in Table 5-27 and is reflective of that assumed in the Residential sector. It was assumed that the technologies historically imported were low efficiency (used technologies, as those described previously for refrigeration). The share of more efficient technologies was assumed to increase slightly over the planning horizon.

The clothes washing end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-27 – Service – clothes washing technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	87.0	100.0	90.0	80.0	80.0
Class C appliance	82.0	0.0	10.0	10.0	10.0
Class B appliance	72.5	0.0	0.0	10.0	10.0
Class A appliance	63.5	0.0	0.0	0.0	0.0
Class A+ appliance	55.5	0.0	0.0	0.0	0.0
Class A++ appliance	49.0	0.0	0.0	0.0	0.0

References: (EC, 2006d; European Commission, 2010a)

The dish washing technology mix is shown in Table 5-28. The rating system of the European Union was adopted for use in this work and it was assumed that the largest share of technologies consists of used imported technologies. A small shift towards more efficient technologies was assumed.

The dish washing end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-28 – Service – dish washing technologies end-use mix: Ghana reference projection

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	91.0	100.0	90.0	80.0	80.0
Class C appliance	85.0	0.0	10.0	10.0	10.0
Class B appliance	75.5	0.0	0.0	10.0	10.0
Class A appliance	67.0	0.0	0.0	0.0	0.0
Class A+ appliance	59.5	0.0	0.0	0.0	0.0
Class A++ appliance	53.0	0.0	0.0	0.0	0.0

References: (de Bruyn and Opschoor, 1997; EC, 2006d; FSEC, 2008; European Commission, 2010b)

The audiovisual technologies assumed consist of television technologies available on the market. These technologies for the Service sector were identical to those in the Residential sector and are shown in Table 5-29.

The audiovisual technology end-use mix shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-29 - Service - audiovisual technologies end-use mix: Ghana reference projection

Technology	Power rating [Watts]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
CRT television	101	90.0	86.0	83.0	78.0
Plasma	361	5.0	7.0	8.5	11.0
LCD	144	5.0	7.0	8.5	11.0
LED LCD	108	0.0	0.0	0.0	0.0
OLED	72	0.0	0.0	0.0	0.0

References: (EC, 2004; CEC, 2009)

The information technologies assumed consisted of desktop and laptop computers in the current work, as shown in Table 5-30.

The information technology end-use mix shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, Section 5.6.1.

Table 5-30 – Service - information technologies end-use mix: Ghana reference projection

Technology	Power rating [Watts]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Desktop computer	150	90.0	70.0	50.0	30.0
Laptop computer	20	10.0	30.0	50.0	70.0

References: (EC, 2004; EFG, 2013)

The Reference Projection for FE demand in the Service sector in Ghana is shown in Figure 5-10. The total FE demand in 2020 reaches 875 ktoe approximately 2.8 times the FE demand in 2008.

The growth in FE demand was attributable to two factors. First was the national GDP which was forecast to nearly double in the period from 2015-2020, Table 5-3. Second was the shift in the economy towards a larger Service sector, a 41% share, by 2020, as presented in Figure 5-5.

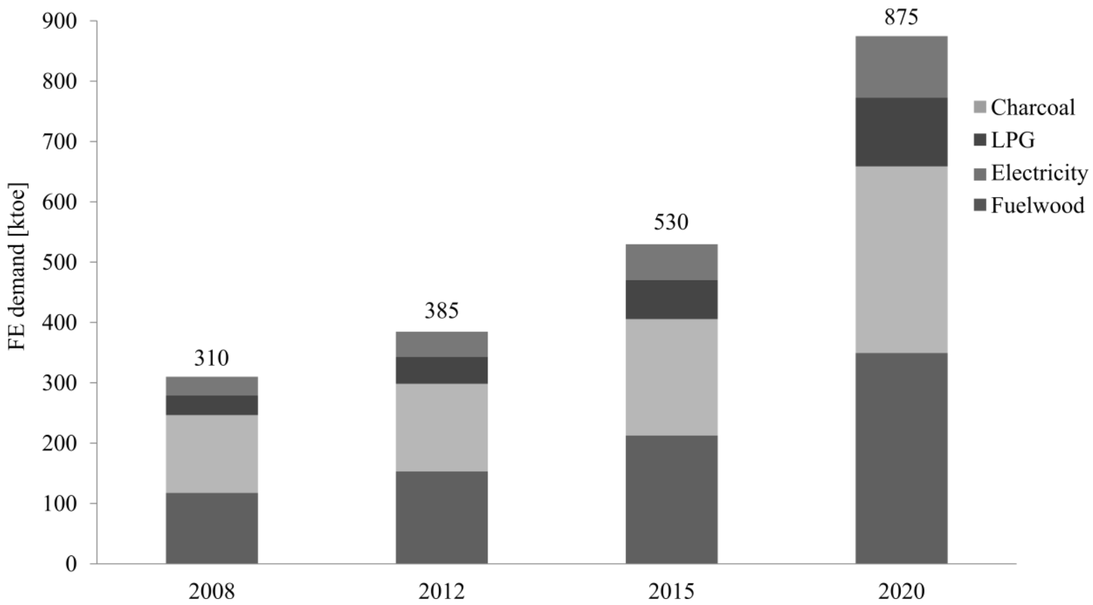

Figure 5-10 - Service sector FE demand reference projection: Ghana reference projection

5.6.3 Industry sector demand

The Industry sector FE demand model for Ghana consisted of the six subsectors of (1) Manufacturing, (2) Aluminum- VALCO, (3) Mining, (4) Construction, (5) Utilities, and (6) Informal manufacturing activities. The total FE demand attributable to each of these subsectors in 2008, the base year, is shown in Table 5-31.

Table 5-31 - Industry - subsectors share of total FE demand: Ghana 2008

Subsectors	Share of total sector FE demand [%]
Informal manufacturing	68.2
Manufacturing	12.6
Aluminum-VALCO	10.9
Mining	6.6
Utilities	1.1
Construction	0.6

Calculations

The Informal Manufacturing sub-sector is seen to represent the predominant share of FE demand in Table 5-31. The Informal Manufacturing FE demand consisted of demand for informal food processing and artisanal craft making, however the fuelwood demand for food processing comprised 99% of the demand of this subsector in the base year according to (EC, 2006d). The total share of FE demand for each of the FE services considered in the Industry sector is shown in Table 5-32.

Formal manufacturing as well as VALCO both represented over 10% of the total FE demand in the base year. The utilities and construction sub-sectors represented smaller shares with less than 2% of total FE demand.

Table 5-32 – Industry - FE services share of total sector FE demand: Ghana 2008

FE Service	Share of total sector FE demand [%]
Cooking & other	69.0
Machine drive	9.7
Process heating	8.0
Electrochemical	7.8
Conventional boilers	2.7
Facility HVAC	1.7
Facility Lighting	0.6
Process cooling and Refrigeration	0.3
Onsite transport	0.2

Calculations

The FE demand model for the Industry sector was discussed previously in Section 4.6.4. The FE demand was forecast based on the EI [ktoe/GVA] of the Industry sector for each FE service and carrier combination within each subsector.

Within each of the industry subsectors a set of nine possible FE services was considered as a proxy in modeling the sub-sectors. This set consisted of (1) conventional boilers, (2) process heating, (3) process cooling & refrigeration, (4) electrochemical, (5) machine drive, (6) facility HVAC, (7) facility lighting, (8) onsite transport, and (9) other services.

Each FE service is provided by end-use technologies that were represented by a Ghana specific representative composite appliance. This appliance was modeled as a mix of technologies and corresponding efficiencies through a weighted sum. The mix of technologies assumed for the current work was assumed to be common for each of the FE service and carrier combinations across all the subsectors unless otherwise specified.

For the majority of FE services in the Industry sector a simple placeholder was used in the share of end-use technologies to model a single technology and representative efficiency which remained constant for the planning horizon. This was done for two reasons. The first consisted of the small relative share that industry represents in total FE demand when fuelwood was excluded. Secondly, the energy services in the sector consist of multiple processes that are difficult to simplify (Haydt, 2012). This together with the lack of information and data regarding the actual FE services and technologies left a small amount of room for improvements.

Conventional boilers are used in industry to produce either heat or steam for a wide array of different processes within the sector (DOE, 2010). The technologies in the end-use mix were place holders as shown in Table 5-33. No change was assumed for the planning horizon for the shares in the end-use technology mix.

Table 5-33 - Industry - conventional boilers technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Local Efficiency [%]	2008	2012	2015	2020
Electricity					
Boiler – standard	100.0	100.0	100.0	100.0	100.0
Diesel					
Boiler – standard	83.0	100.0	100.0	100.0	100.0
RFO					
Boiler – standard	83.0	100.0	100.0	100.0	100.0

References: (ESMAP, 1992; Banerjee et al., 2012; Haydt, 2012)

Process heating in the industrial sector is the act of raising or maintaining the heat of a substance that is used in a manufacturing activity. This may include melting scrap metal or processing food for packaging (DOE, 2010). The technology mix shown in Table 5-34 contains place holders for the planning horizon. No change was assumed for the planning horizon for the shares in the end-use technology mix.

Table 5-34 - Industry - process heating technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Local Efficiency [%]	2008	2012	2015	2020
Electricity					
Heater – standard	100.0	100.0	100.0	100.0	100.0
Diesel					
Heater – standard	100.0	100.0	100.0	100.0	100.0
RFO					
Heater – standard	100.0	100.0	100.0	100.0	100.0

References: Assumed

Process cooling and refrigeration consists primarily of motor driven systems that drive the compressors, fans and pumps used (DOE, 2010). Electric motors were therefore assumed as a proxy for technologies that use electricity in the subsector. A mix of motor capacities was assumed based on the work from Haydt (2012) on end-use efficiency. The end-use technology mix shown in Table 5-35 considered motors of different capacities. The technologies that utilize diesel and RFO are assumed as place holders. No change was assumed in the end-use technology mix for the planning horizon.

Table 5-35 – Industry - process cooling & refrigeration technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Electricity					
Motor 0<0.75kW	64.0	1.0	1.0	1.0	1.0
Motor 0<0.75kW -Efficient	84.0	0.0	0.0	0.0	0.0
Motor 0.75<4kW	75.0	7.0	7.0	7.0	7.0
Motor 0.75<4kW-Efficient	86.9	0.0	0.0	0.0	0.0
Motor 4<10kW	85.0	8.0	8.0	8.0	8.0
Motor 4<10kW-Efficient	90.0	0.0	0.0	0.0	0.0
Motor 10<30kW	89.0	13.0	13.0	13.0	13.0
Motor 10<30kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 30<70kW	91.0	20.0	20.0	20.0	20.0
Motor 30<70kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 70<130kW	92.0	12.0	12.0	12.0	12.0
Motor 70<130kW-Efficient	95.2	0.0	0.0	0.0	0.0
Motor 130<500kW	93.0	22.0	22.0	22.0	22.0
Motor 130<500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Motor >500kW	95.0	17.0	17.0	17.0	17.0
Motor >500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Diesel					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
RFO					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: (Haydt, 2012) and assumptions

Electrochemical end-uses are predominantly within the VALCO aluminum manufacturing sector and consist of the use of electricity to cause a chemical reaction such as the reduction of alumina to aluminum and oxygen (EC, 2006d; DOE, 2010). The end-use mix for electrochemical processes, shown in Table 5-36, consisted of a placeholder for the planning horizon. No change in efficiency was assumed.

Table 5-36 - Industry - electrochemical technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Electricity					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: Assumed

Machine drive in the current work consists of energy carrier and technology combinations with electricity, diesel and RFO as shown in the end-use technology mix in Table 5-37. Machine drive consists of the driving of motor driven systems through the conversion of electricity or heat (DOE, 2010). A mix of electric motor capacities was considered in the current work together with their efficient alternative. Place holders were assumed for both diesel and RFO fueled technologies. No change was assumed along the planning horizon in the end-use technology mix for the Reference Projection.

Table 5-37 – Industry - machine drive technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Electricity					
Motor 0<0.75kW	64.0	1.0	1.0	1.0	1.0
Motor 0<0.75kW -Efficient	84.0	0.0	0.0	0.0	0.0
Motor 0.75<4kW	75.0	7.0	7.0	7.0	7.0
Motor 0.75<4kW-Efficient	86.9	0.0	0.0	0.0	0.0
Motor 4<10kW	85.0	8.0	8.0	8.0	8.0
Motor 4<10kW-Efficient	90.0	0.0	0.0	0.0	0.0
Motor 10<30kW	89.0	13.0	13.0	13.0	13.0
Motor 10<30kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 30<70kW	91.0	20.0	20.0	20.0	20.0
Motor 30<70kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 70<130kW	92.0	12.0	12.0	12.0	12.0
Motor 70<130kW-Efficient	95.2	0.0	0.0	0.0	0.0
Motor 130<500kW	93.0	22.0	22.0	22.0	22.0
Motor 130<500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Motor >500kW	95.0	17.0	17.0	17.0	17.0
Motor >500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Diesel					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
RFO					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: (Haydt, 2012) and assumptions

HVAC consists of heating, ventilation and air conditioning of space within the building envelope (DOE, 2010). Due to the geography and climate of Ghana heating of building spaces is not common, however it may be required in specific industries that require certain constant temperatures. Similar to process cooling and refrigeration the HVAC FE services consist primarily of motor driven systems that drive the compressors, fans and pumps used in addition to heat which may be provided by conventional boilers. Electric motors were assumed as a proxy for technologies that used electricity in the subsector. The end-use technology mix in Table 5-38 considers motors of different capacities and their efficient alternatives. The technologies that utilize diesel and RFO were assumed as place holders. No change was assumed in the end-use technology mix for the planning horizon in the Reference Projection.

Facility lighting was assumed to consist of indoor and outdoor lighting technologies used for illumination of environments (e.g. office space and assembly room space) within the industry boundaries (DOE, 2010). The lighting end-use technology mix for the Reference Projection is shown in Table 5-39.

A shift is seen, in Table 5-39, towards more efficient lighting for technologies as in the other FE sectors (i.e. Residential and Service), due to previously described national efforts to phase out inefficient incandescent lamps (EC, 2009b, 2015a). A 2 pp annual decrease in the end-use mix share for incandescent lamps was assumed, which led to an increase in CFL lamps. A 2 pp increase was assumed annually in the share for T8 and T5 lamps systems due to a decrease in the end-use mix share of T12 lamps. No change was assumed in lighting technologies which are more specific to industrial facilities (e.g. high pressure sodium and mercury vapor lamps).

Table 5-38 - Industry - HVAC technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Electricity					
Motor 0<0.75kW	64.0	1.0	1.0	1.0	1.0
Motor 0<0.75kW -Efficient	84.0	0.0	0.0	0.0	0.0
Motor 0.75<4kW	75.0	7.0	7.0	7.0	7.0
Motor 0.75<4kW-Efficient	86.9	0.0	0.0	0.0	0.0
Motor 4<10kW	85.0	8.0	8.0	8.0	8.0
Motor 4<10kW-Efficient	90.0	0.0	0.0	0.0	0.0
Motor 10<30kW	89.0	13.0	13.0	13.0	13.0
Motor 10<30kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 30<70kW	91.0	20.0	20.0	20.0	20.0
Motor 30<70kW-Efficient	94.1	0.0	0.0	0.0	0.0
Motor 70<130kW	92.0	12.0	12.0	12.0	12.0
Motor 70<130kW-Efficient	95.2	0.0	0.0	0.0	0.0
Motor 130<500kW	93.0	22.0	22.0	22.0	22.0
Motor 130<500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Motor >500kW	95.0	17.0	17.0	17.0	17.0
Motor >500kW-Efficient	96.0	0.0	0.0	0.0	0.0
Diesel					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
RFO					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: (Haydt, 2012) and assumptions

Onsite transportation technologies consist of vehicles and other transportation equipment that moves materials and people within the Industry boundaries (DOE, 2010). The onsite transportation end-use mix in Table 5-40 consists of place holders for technologies associated with all FE carriers. No change was assumed through the planning horizon for the shares in the end-use mix of technologies.

Other services considered for the current work consisted of other energy use processes not covered by the previously described services. The end-use technology mix is shown in Table 5-41. The predominant other services considered here were the food processing and cooking with fuelwood from the informal manufacturing sector. The fuelwood technologies were assumed to consist of traditional fuelwood cooking technologies. Placeholders were assumed and held constant for the planning horizon, assuming no change in the shares of the end-use mix of technologies.

Table 5-39 – Industry - facility lighting technologies end-use mix: Ghana reference projection

Technology	Efficacy [lumens/Watt]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Incandescent lamp (100 W)	12.0	12.0	10.0	8.0	6.0
CFL	67.0	0.0	2.0	2.0	4.0
Fluorescent F40T12 4’ 34 W + magnetic ballast system	80.0	32.0	8.0	26.0	22.0
Fluorescent F32T8 4’ 32 W + electronic ballast system	90.0	6.0	8.0	10.0	12.0
Fluorescent F28T5 4’ 28 W + electronic ballast system	100.0	0.0	2.0	4.0	6.0
LED lamp	94.0	0.0	0.0	0.0	0.0
LED tube lamp	100.0	0.0	0.0	0.0	0.0
Low pressure sodium lamp	145.0	12.5	12.5	12.5	12.5
High Pressure Sodium Lamp	105.0	12.5	12.5	12.5	12.5
Mercury Vapor (HID) lamp	36.5	12.5	12.5	12.5	12.5
Metal halide lamp	100.0	12.5	12.5	12.5	12.5

References: (Constantine et al., 1999; EC, 2009b, 2004)

Table 5-40 - Industry - onsite transport technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
Diesel					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
RFO					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: Assumed

Table 5-41 - Industry - other services technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	31.0	28.0	23.0
Improved fuelwood stove	32.5	5.0	13.0	19.0	29.0
Traditional mud stove	17.5	60.0	56.0	53.0	48.0
Electricity					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
Diesel					
Unspecified technology	100.0	100.0	100.0	100.0	100.0
RFO					
Unspecified technology	100.0	100.0	100.0	100.0	100.0

References: (EC, 2004, 2006d)

The Reference Projection FE demand for the Industry sector is presented in Figure 5-11. FE demand is seen to rise from 2,136 ktoe in 2008 to an aggregate demand of 5,595 ktoe in 2020 which represents approximately 3.8 times the base year demand. The large growth in FE demand visible between the years 2015 and 2020 is reflective of the projected national GDP which was forecast to grow 170% over the period as shown in Table 5-3.

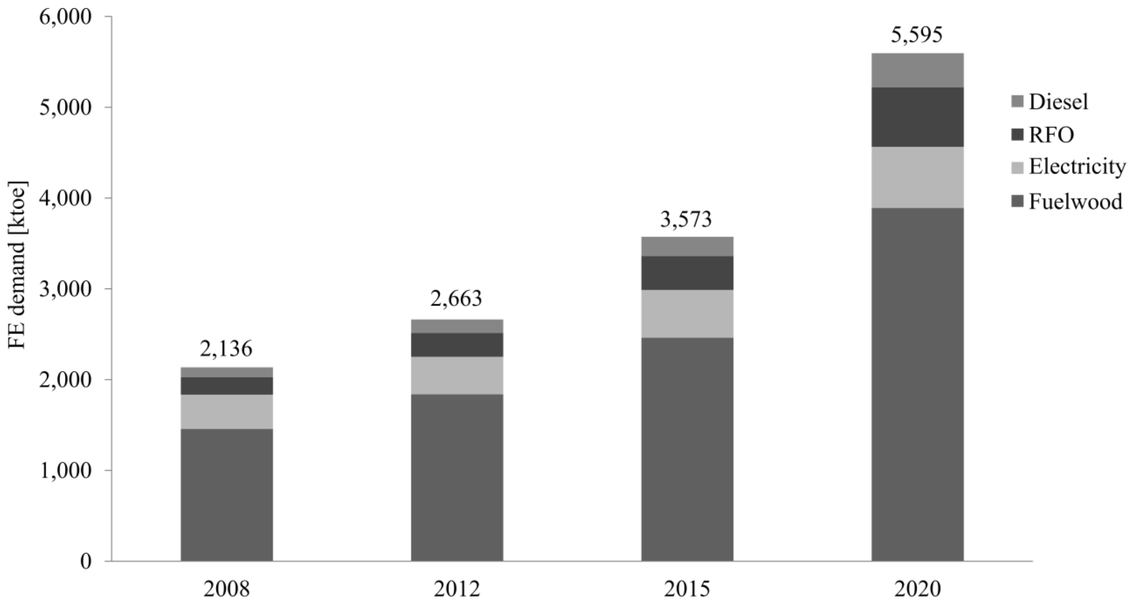

Figure 5-11 - Industry sector FE demand reference projection: Ghana reference projection

5.6.4 Transport sector demand

The Transport sector model for Ghana consisted of the six subsectors of (1) Road, (2) Rail, (3) Water – domestic, (4) Water - international (5) Air- domestic, and (6) Air – international. Each of the subsectors was disaggregated into passenger and freight transport where applicable. Road transport specifically was modeled to reflect the collective and private passenger transport demand of the subsector. The share of FE demand attributable to each of the subsectors is shown in Table 5-42.

The Road transport sub-sector is seen to represent the dominant share of FE demand in the sector with a share of 89%. The remaining FE demand sectors each represent less than 7.5% of total FE demand.

The FE demand attributable to each of the transport modes for passenger and freight are shown in Table 5-43. Here the transport modes were disaggregated into freight and passenger travel. The FE demand for private passenger transport vehicles represented 32% of total FE demand. Following private passenger transport, the minibus “trotro” transport mode represented the second largest share of demand. The freight transport “light vehicle” mode represented the third largest FE demand in the sector.

Table 5-42 – Transport - subsectors share of total FE demand – Ghana 2008

Subsectors	Share of total sector FE demand [%]
Road	88.9
Air- international	6.4
Water- domestic	3.7
Air- domestic	0.7
Rail	0.3
Water- international	0.0

Calculations

Rail transport of passengers and freight represented the smallest shares of FE demand. The railroad lines historically formed a triangle serving Kumasi in the north, Accra and Tema in the East and Takadori in the West, totaling approximately 947 km (EC, 2006d; Bullock, 2009). The railway has been mostly abandoned since the 1990s and only a small portion of the original line is in operation providing passenger and freight transport to a small area surrounding Accra (RT, 2015). Currently in Ghana long distance domestic transport consists primarily of large buses, planes and private vehicles for passengers and heavy and medium trucks for freight (EC, 2006d).

Water transport by boat consists of ferry transport in the freshwater lake created by the Akosombo dam. Ferry transport consists of both passenger and freight transport along the length of the lake (North-South) as well as traversing (East-West) the lake (MoT, 2011). International and passenger and freight transport ships, while stopping in the ports of Ghana were reported to not seek bunkering services there and therefore were not considered here, as discussed in Appendix B.

The FE demand is forecast based on the EI [ktoe/pkm or ktoe/tkm] of the Transport sector for each transport type and carrier combination within each subsector.

The Transport sector mobility is provided by end-use technologies, or vehicles, which were represented by a Ghana specific representative composite technology. This technology was modeled with a mix of technologies and corresponding efficiencies through a weighted sum. The mix of technologies assumed for the current work is presented in Appendix B, which details the mobility level in the Transport sector.

The FE demand model for the Transport sector is discussed in detail in Appendix B and not repeated here. The technology mix for all the end-use types was assumed to remain constant for the planning horizon within the reference projection as were the shares that each mode represents of the total pkm and tkm.

Table 5-43 – Transport - FE services share of total sector FE demand – Ghana 2008

Transport modes	Share of total sector FE demand [%]
Passenger	
Private car	32.3
Minibus (Trotro)	17
Bus	8.5
Taxi	7.8
Plane	3.9
Boat	1.8
Train	0.2
Freight	
Light vehicle (road)	13.5
Medium vehicle (road)	6.8
Plane	3.2
Heavy vehicle (road)	3
Boat	1.8
Train	0.2

Calculations

To develop a projection of the FE demand from the sector, considerations regarding the growth in the mobility for the sector were required. The mobility, or demand for movement of passengers and freight were measured through pkm and tkm respectively. The EC et al. (2001) assumed a growth rate in demand for passenger travel and freight travel of 0.025% and 0.04% annually. The mobility relative to the base year for passenger and freight transport is shown in Table 5-44.

Table 5-44 - Mobility growth for Transport sector - Ghana

	Growth in mobility relative to base year			
Transport type	2008	2012	2015	2020
Passenger [2.5% /year]	1	1.10	1.19	1.34
Freight [4.0% /year]	1	1.17	1.32	1.60

References: (EC et al., 2001)

The Reference Projection for FE demand in the Transport sector is shown in Figure 5-12. With the growth in mobility rates assumed for this work FE demand reaches 2,921 ktoe by 2020.

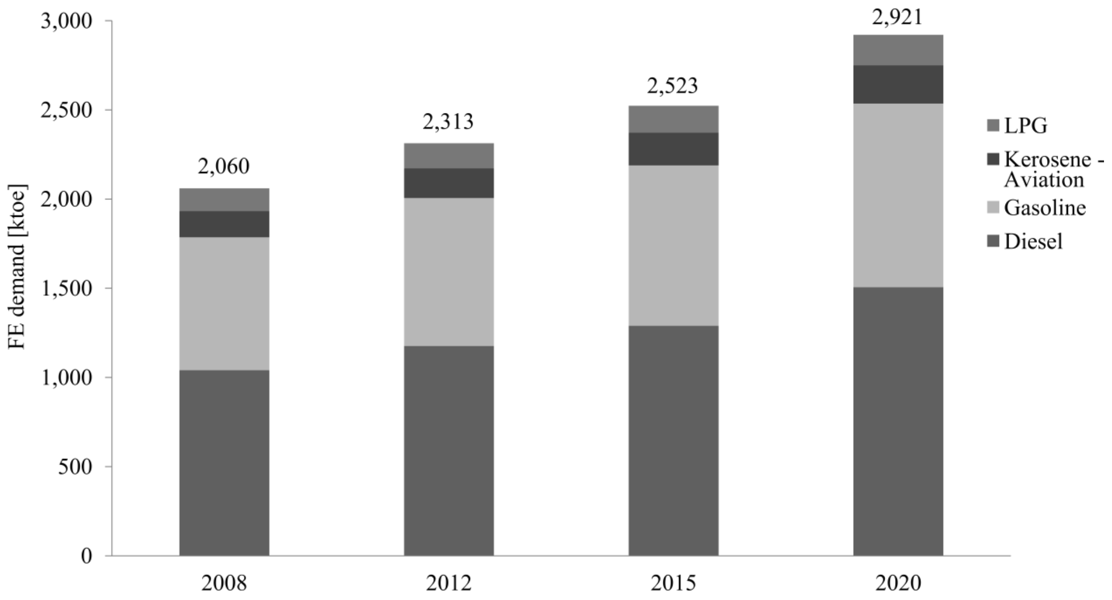

Figure 5-12 - Transport sector FE demand reference projection: Ghana reference projection

5.6.5 Agriculture and Fishery sector demand

The Agriculture and Fishery sector in Ghana was modeled as consisting of 12 FE services. The Agriculture and Fishery sector, as a productive sector, consists of FE services for adding value to products. The FE services were (1) fish smoking, (2) pumping, (3) spraying, (4) lighting, (5) refrigeration, (6) milling, (7) heating, (8) sawing, (9) drying, (10) transport – internal agriculture, (11) transport – large marine fishing vessels, (12) transport – small marine & freshwater fishing vessels. The shares in total FE demand that each of these services represent is shown in Table 5-45.

Transport for fishing both in freshwater and marine bodies of water are seen to represent the largest shares of total FE demand in the sector. Drying of agricultural goods (e.g. cocoa and shea butter seeds), as well as fish for preservation represents 10% of total demand. Drying is, however, majorly accomplished with direct solar thermal heat. Smoking of fish for preservation is accomplished with the use of fuelwood and represented 7% of total demand in the sector. The remaining FE services represented less than 4.5% of total FE demand individually.

Table 5-45 - Agriculture & Fishery - FE services share of total sector FE demand - Ghana 2008

FE Service	Share of total sector FE demand [%]
Transport – large marine vessels	36.6
Transport – small marine & freshwater vessels	36.6
Drying	10.2
Smoking (fish)	7.2
Spraying	4.4
Transport-internal	2.2
Pumping	1.3
Sawing	0.6
Refrigeration	0.4
Lighting	0.3
Milling	0.2
Heating	0.1

Calculations

The FE demand model for the Agriculture and Fishery sector was detailed in 4.6.6. FE demand is forecast based on the EI [ktoe/GVA] of the Agriculture and Fishery sector for each FE service and carrier combination. The FE service is provided by end-use technologies which are represented by a Ghana specific representative composite appliance. This appliance was modeled as a mix of technologies and corresponding efficiencies through a weighted sum.

One method of fish preservation in Ghana consists of smoking with fuelwood fired technologies. The traditional common smoker technology and a large capacity efficient smoker are both shown in the end-use technology mix in Table 5-46. Efficient technologies were assumed to make up a small share, 5%, of the mix by 2020.

Table 5-46 - Agr. & Fish. - smoking technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
Smoker “Chorkkor” type	39.0	100.0	100.0	100.0	95.0
Smoker Large capacity – efficient	48.0	0.0	0.0	0.0	5.0

References: (EC, 2004, 2006d), assumptions

Water pumping for irrigation purposes in the agriculture sector consists of diesel and electrical pumps as shown in the mix in Table 5-47. A small shift, 1 pp annual increase of end-use mix share, towards more efficient pump alternatives was assumed over the planning horizon as shown.

Table 5-47 - Agr. & Fish. - pumping technologies end-use mix: Ghana reference projection

Technology	Efficiency [kWh/Acre-ft] [diesel gallon/ Acre-ft]	Share in end-use mix [%]			
		2008	2012	2015	2020
Electricity					
Water pump- Inefficient	305.7	80.0	76.0	73.0	68.0
Water pump- Efficient	203.8	20.0	24.0	27.0	32.0
Diesel					
Water pump- Inefficient	27.1	20.0	24.0	27.0	32.0
Water pump- Efficient	16	80.0	76.0	73.0	68.0

References: (EC, 2006d; APEP, 2015), assumptions

Spraying consists of the spraying of pesticides, primarily for cocoa plantations. It was assumed that this was done through a portable premix gasoline fueled sprayer, Table 5-48. There was no change assumed for the share in the end-use mix in the planning horizon.

Table 5-48 - Agr. & Fish. - spraying technologies end-use mix: Ghana reference projection

Technology	Power [kW]	Share in end-use mix [%]			
		2008	2012	2015	2020
Premix gasoline					
Portable sprayer	2.9	100.0	100.0	100.0	100.0

References: (EC, 2006d; STIHL, 2015), assumptions

The indoor and outdoor lighting technologies, which comprised the end-use mix, are shown in Table 5-49. The mix of technologies reflects that presented in the Industry sector. As in the previous sectors a shift towards the more efficient lighting technologies of CFLs and away from incandescent lamps was assumed due to national programs for standards and labeling.

Incandescent lamp technologies were assumed to be phased out by 2020 and their share in the end-use mix decreased with a constant annual rate of decline of 25% (of share value) annually. CFL lamps were assumed to replace the decreasing share of incandescent lamps. A shift was assumed from T12 fluorescent magnetic ballast lamps, 2 pp annually, to T8 lamps until 2020. The share of T5 lamps increased 1 pp annually from 2015 to 2020. A small share of the mix was assumed to be made of LED lamps by 2020.

The refrigerators assumed reflected those present in the Residential and Service sectors. A shift is seen towards more efficient technologies over the planning horizon as a result of refrigerator energy efficiency guide labels and standards in Ghana (Ben Hagan, 2007; Van Buskirk et al., 2007).

The refrigeration end-use mix technology shares, for the base year and the planning horizon, were assumed to be identical to the assumptions made for the Residential sector, see Section 5.6.1.

Table 5-49 - Agr. & Fish. - lighting technologies end-use mix: Ghana reference projection

Technology	Efficacy [lumens/Watt]	Share in end-use mix [%] 2008	2012	2015	2020
Indoor lighting					
Electricity					
Incandescent lamp	12.0	34.0	0.11	0.05	0.00
CFL	67.0	65.0	0.57	0.51	0.36
Fluorescent F40T12 4’ 34W + magnetic ballast system	80.0	0.0	0.08	0.14	0.24
Fluorescent F32T8 4’ 32W + electronic ballast system	90.0	0.0	0.00	0.00	0.05
Fluorescent F28T5 4’ 28W + electronic ballast system	100.0	1.0	0.24	0.30	0.34
LED lamp	94.0	0.0	0.0	0.0	0.01
LED 4' lamp	100.0	0.0	0.0	0.0	0.0
Outdoor lighting					
Electricity					
Low pressure sodium lamp	145.0	10.0	14.0	17.0	22.0
High Pressure Sodium Lamp	105.0	30.0	26.0	23.0	18.0
Mercury Vapor (HID) lamp	36.5	60.0	60.0	60.0	60.0
Metal halide lamp	100.0	34.0	11.0	5.0	0.0

References: (EC, 2004; Constantine et al., 1999; Agyarko, 2013; REEEP, 2015)

Feed-milling technologies were assumed to consist of electric feed milling appliances as shown in Table 5-51. A placeholder for efficient and standard technologies was assumed for the current work.

A small shift towards more efficient technologies was assumed at 1 pp a year, along the planning horizon.

Table 5-50 - Agr. & Fish. - refrigeration technologies end-use mix: Ghana reference projection

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Refrigerator[1] prior to regulation	100	80.0	72.0	66.0	56.0
1 Star[2] refrigerator	95	10.0	16.0	20.5	28.0
2 Star refrigerator	82.5	10.0	11.2	121	13.6
3 Star refrigerator	65	0.0	0.0	0.0	0.0
4 Star refrigerator	48.5	0.0	0.8	1.4	2.4
5 Star refrigerator	41	0.0	0.0	0.0	0.0

1. All are assumed to be combined Refrigerator +Freezer
2. Star rating refers to the energy efficiency standards and labeling regulations of Ghana (MoE, 2009b).
References: (EC, 2006d; MoE, 2009b), assumptions

Table 5-51 - Agr. & Fish. - refrigeration technologies end-use mix: Ghana reference projection

Technology	Efficiency[1] [%]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Feed milling –Standard	125.0	80.0	76.0	73.0	68.0
Feed milling –Efficient	100.0	20.0	24.0	27.0	32.0

1. Assumed relative efficiencies

References: (EC, 2006d), assumptions

The heating of indoor spaces is not a FE service in Ghana due to the climate, however heating of indoor spaces is required for certain industries as well as agricultural practices. Here heating is required in commercial poultry farms for hatchery and enclosure heating (EC, 2006d). Heating at poultry farms does not require high temperatures and is typically done through heating lamps as shown in the technology mix in Table 5-52. No change was assumed for the share in the end-use mix along the planning horizon.

Table 5-52 - Agr. & Fish. - heating technologies end-use mix: Ghana reference projection

Technology	Power [W]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Infrared heat lamp	175.0	100.0	100.0	100.0	100.0

References: (EC, 2006d; GVPS, 2014), assumptions

Forestry in the agriculture sector consists of activities for fuelwood as well as products for domestic use and export. Ghana has a diverse timber stock, which provides for an active timber industry (FCG, 2015a, 2015b). The mix of electric and premix gasoline saws assumed for the technology mix are shown in Table 5-53.

The saw efficiencies assumed are placeholders. A small shift towards more efficient technologies at 1 pp a year was assumed in the planning horizon.

Table 5-53 - Agr. & Fish. - sawing technologies end-use mix: Ghana reference projection

Technology	Power [W]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Saw motors – Standard	125.0	80.0	76.0	73.0	68.0
Saw motors – Efficient	100.0	20.0	24.0	27.0	32.0
Premix gasoline					
Saw motors – Standard	125.0	80.0	76.0	73.0	68.0
Saw motors – Efficient	100.0	20.0	24.0	27.0	32.0

References: (EC, 2006d), assumptions

Drying of agricultural crops including corn, cocoa, and shea butter seeds is typically accomplished through the traditional solar thermal drying technique. The technology mixes assumed for electric and solar thermal drying are shown in Table 5-54.

A shift towards more efficient electric dryer technologies of 1 pp a year was assumed in the planning horizon. No change in the end-use mix, for traditional direct solar-thermal drying technologies, was assumed for the planning horizon.

Table 5-54 - Agr. & Fish. - drying technologies end-use mix: Ghana reference projection

Technology	Power [W]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Mechanical dryer – standard	0.34	10.0	14.0	17.0	22.0
Mechanical dryer – efficient	0.51	90.0	86.0	83.0	78.0
Direct solar – thermal	Efficiency [%]				
Traditional drying technique	100.0	100.0	100.0	100.0	100.0

References: (EC, 2006d; Kallai, 2011), assumptions

Internal transport in the Agriculture and Fishery sector consists of utility trucks as well as tractors. The technology mix assumed for internal transport with diesel vehicles is shown in Table 5-55. A small increase in the share of more efficient vehicles was assumed over the planning horizon.

A shift towards more efficient internal transport technologies of 1 pp a year was assumed for the planning horizon.

Table 5-55 – Agr. & Fish. -internal transport - technologies end-use mix: Ghana reference projection

Technology	Power [gallons/acre] [l/100km]	Share in end-use mix [%] 2008	2012	2015	2020
Diesel					
	[gallons/acre]				
Tractor – standard	2.65	90.0	86.0	83.0	78.0
Tractor – efficient	1.26	10.0	14.0	17.0	22.0
	[l/100km]				
Truck – standard	12.84	90.0	86.0	83.0	78.0
Truck – efficient	11.20	10.0	14.0	17.0	22.0

References: (Grisso et al., 2004; EC, 2006d; Fuelly, 2015), assumptions

Internal transport within the Fishery sector consists of fishing vessels with either diesel or premix gasoline motors. The technology mixes for both large marine fishing vessels as well as small marine and freshwater vessels are shown in Table 5-56 and Table 5-57. A small increase in the share of more efficient motors was assumed over the planning horizon.

A shift towards more efficient large marine fishing vessel motors of 1 pp a year was assumed for the planning horizon. The same assumptions applied to the end-use mix of small marine and freshwater fishing vessel motors, for the planning horizon.

Table 5-56 – Agr. & Fish. - transport - Large marine fishing vessels - technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Diesel					
Motor inboard – 70hp – Standard	30.0	80.0	76.0	73.0	68.0
Motor inboard – 70hp – Efficient	40.0	20.0	24.0	27.0	32.0
Premix gasoline					
Motor inboard – 70hp – Standard	20.0	80.0	76.0	73.0	68.0
Motor inboard – 70hp – Efficient	27.0	20.0	24.0	27.0	32.0

References: (EC, 2006d; Klaxon, 2015), assumptions

The Agriculture and Fishery sector represented the smallest share in total FE demand in 2008 in Ghana, and this remains so until 2020 in the reference projection. The total FE demand reaches 519 ktoe, as shown in the reference projection for the sector in Figure 5-13.

Table 5-57 – Agr. & Fish. - transport - Small marine and freshwater fishing vessels - technologies end-use mix: Ghana reference projection

		Share in end-use mix [%]			
Technology	Efficiency [%]	2008	2012	2015	2020
Diesel					
Motor outboard – 36hp – Standard	23.0	80.0	76.0	73.0	68.0
Motor outboard – 36hp – Efficient	31.0	20.0	24.0	27.0	32.0
Premix gasoline					
Motor outboard – 36hp – Standard	16.0	80.0	76.0	73.0	68.0
Motor outboard – 36hp – Efficient	21.0	20.0	24.0	27.0	32.0

References: (EC, 2006d; Klaxon, 2015), assumptions

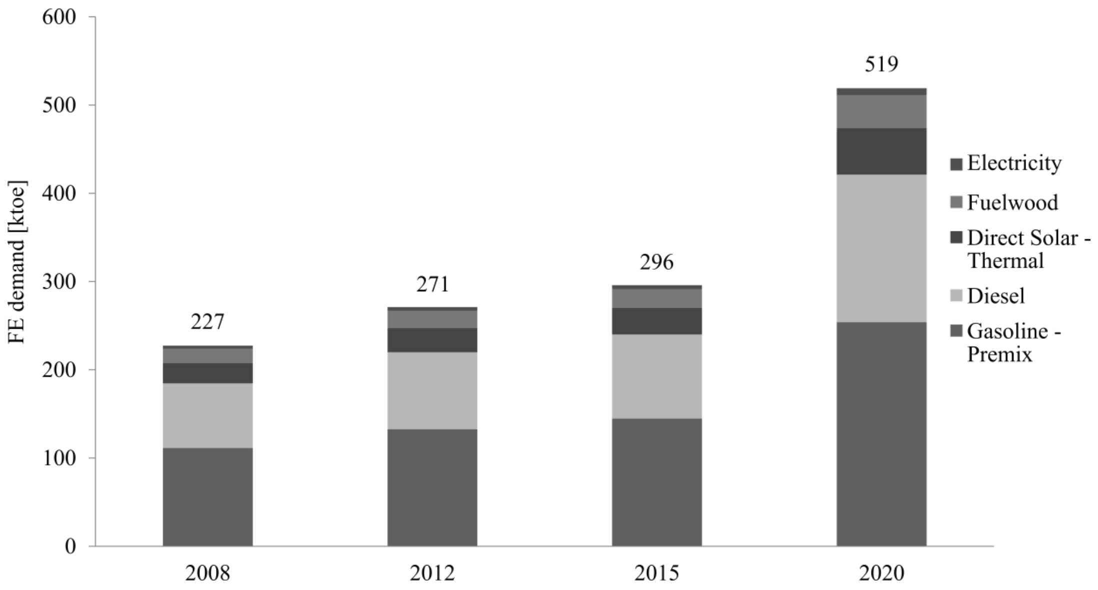

Figure 5-13 – Agr. & Fish. sector FE demand reference projection: Ghana reference projection

5.7 PE supply and transformation

5.7.1 PE supply

The PE supply and energy flows through the modeled national energy system of Ghana, for the base year 2008 and the final year of the planning horizon 2020, are shown in the Sankey diagrams in Figure 5-20 and Figure 5-21.

The PE supply in the base year of 2008 was predominantly from indigenous PE resources representing 74% of the PE supply. Imports, which consisted of fossil fuel resources, represented the remaining share of the PE supply.

The indigenous PE supply was dominated by biomass resources destined for use as fuelwood or as an input for charcoal production. Over 50% of the biomass PE supply was required to meet FE demand for charcoal. The remainder of indigenous supply was composed of large hydro resources in additional to other renewables consisting of small wind and biofuels and wood wastes for electricity generation. Additionally, there was a share of direct solar thermal that was not transformed as it was used for drying in the Agriculture and Fishery sector.

Ghana is seen here to be completely dependent on PE imports for the fossil fuel resources of natural gas, crude oil and other petroleum products. Natural gas and crude oil represented the largest shares of imported PE supply representing approximately 38% and 34% respectively.

Crude oil imports provided for the refinery transformation processes. Refinery petroleum product outputs were supplemented with their imported equivalents to meet FE demand.

Ghana imported natural gas via the WAGP to meet the requirements for electricity generation supply for the national grid.

5.7.1.1 Indigenous PE Resources

Fossil fuels

This work did not take a prescient view of the discovery of indigenous PE resources and all fossil fuels were assumed to be imported. In the base year of 2008 there were no significant indigenous petroleum resources in Ghana, and all crude oil for refining was imported (EC, 2006c).[17]

At the time of publishing the Strategic National Energy Plan in 2006, Ghana did not have any significant domestic resources or production of natural gas. The current work did not assume or model the possible discovery of domestic natural gas resources. Therefore 100% of natural gas was assumed to be imported via the WAGP (EC, 2006c). The capacity of the WAGP was stated to be 460 Million standard cubic feet per day (MMSCFD) and serves the countries of Ghana, Benin and Togo with an origin in Nigeria (WAPCo, 2015). No constraints were assumed on natural gas imported through the WAGP in Ghana. Allowing for imports to surpass actual WAGP constraints in the model allowed for planners to understand the PES requirements for a given EP alternative.

The case study country, Ghana, to date does not have any domestic coal resources (UN-ENERGY et al., 2006). The current work did not assume or model the possible discovery of domestic coal resources.

Renewables

The solar energy resources in Ghana are spread throughout the national land mass. Daily solar radiation levels range from 4 to 6 kWh/m^2 with the highest radiation levels in the northern region covering approximately 60% of the total land mass (MoP, 2015). According to MoP (2015) the annual hours of direct solar radiation range from 1,800 to 3,000 hours.

Approximately two-thirds of Ghana is covered by forested area, or 18.3 million hectares. Biomass potential was estimated at 65,000 GWh/year of exploitable biomass fuels consisting

[17] Since 2007 oil exploration activities have found proven reserves of oil and gas in the waters south of Takoradi in the Jubilee field, and extraction activities have begun (TO, 2015). The first phase of the Jubilee project is expected to produce 120,000 bpd of oil and 140 MMSCFD of gas (AfDB, 2009). Prior to the extraction from Jubilee field as described above, for petroleum resources, no natural gas resources were known to exist in Ghana (UN-ENERGY et al., 2006).

of fuelwood from existing tropical forests (MoP, 2015). These resources can be exploited for fuelwood, charcoal production or electricity and heat generation.

On-shore wind resources were estimated to be sufficient for approximately 5,640 MW of total potential installed wind generation capacity in an area covering 1,128 km^2 (MoP, 2015).

Off-shore wind resources, while not explicitly stated in MoP (2015) were estimated, in this work, to be 75% of total on-shore resources. In total 4,230 MW of potential off-shore wind capacity was assumed for Ghana.

Total potential exploitable hydro-power resources have been estimated to be approximately 2,500 MW, of which 1,180 MW has been developed at Akosombo and Kpong sites (MoP, 2015).

Small hydro sites consisting of 1 MW or less have been identified throughout the country totaling 2.64 MW (Ahiataku-Togobo and Amankwa, 2006).

Marine based energy resources were assumed to include two resource types. These were (1) tidal and (2) wave resources for electricity generation. The total resources in Ghana were assumed based on planned installation activities of a 1,000 MW wave power project (Subsea, 2014). This project was assumed to be 50% of total exploitable capacity, 2,000 MW, within the planning horizon for wave power. Total exploitable tidal power resources were assumed to be equal to wave power resources.

No study has been completed to characterize geothermal resources in Ghana, and geothermal resources were not assumed in the current work (Afribiz, 2013).

5.7.2 Charcoal production

More than half of the biomass PE resources in the base year were destined for charcoal transformation processes, as shown in the energy flow diagram for Ghana in 2008 in Figure 5-20.

In the reference projection charcoal transformation was exclusively completed with the traditional earth mound production technique. This resulted in substantial losses due to the low efficiency of this traditional technique, described previously in Section 4.7.2.

5.7.3 Petroleum refinery

Imported crude oil provided for the supply requirements of the petroleum refinery. The TOR provides for FE demand for petroleum products, as detailed in Section 4.7.3.

The TOR production capacity remained unchanged for the planning horizon in the Reference Projection. As the TOR was unable to meet domestic demand for petroleum products in the base year it remained unable to do so for the Reference Projection and additional demand was met through increased imports.

5.7.4 Electricity generation

5.7.4.1 National Grid

The PE supply for electricity generation for the national grid is shown in Figure 5-20 to consist of natural gas, hydro and a small share of other renewables.

The total installed capacity in 2008 was 2,587 MW. The modeled installed capacity in the base year is broken down into natural gas, hydro and other renewable supply type technologies in Table 5-58.

Table 5-58 – Installed electricity generation capacity - National grid: Ghana 2008

Electricity generation technology	Installed capacity [MW]	Share of electricity generated [%]
Natural gas		
"TAPCO"[1] gas turbine	330	11.18
"TICO"[2] gas turbine	330	11.18
Osagyefo Power Barge gas turbine	125	4.69
Tema CCGT	110	4.12
Distributed generic gas turbines	150	5.62
SAPP[3] CCGT	180	5.53
CENIT gas turbine	110	4.57
Hydro-electric		
Akosombo dam	1,038	45.47
Kpong dam	160	7.00
Wind		
Generic wind farm	50	0.50
Other renewables		
Unspecified generic small wind installations	1	0.04
Biofuels & wood waste	3	0.10
Imports	-	-
Total installed capacity	**2,587**	**-**

1. Takoradi Power Company (TAPCO)
2. Takoradi International Company (TICO)
3. Sunon Asogli Power Plant (SAPP)

Installed generation capacity was expanded in an effort to sufficiently meet the growth in electricity demand from the FE demand sectors. In the Reference Projection this increased installed capacity was chosen to follow the installed capacity types that were considered in the main electricity supply alternative in the Ghana SNEP from EC (2006b).

Due to differing assumptions regarding electricity demand the Reference Projection of the current work did not follow the forecast of the SNEP. The electricity demand in the current work was modeled based on the data provided in the SNEP, however differences existed. These differences included but were not limited to the following. Three population types were used to model the demand in the current work as opposed to two in SNEP. The share that each FE service represented of total FE demand were assumed in this work. Assumptions were required for the mix of end-use technologies and ownership levels which may have differed from the SNEP assumptions. Finally, the most significant difference was that the Reference Projection assumed a continuation of business as usual growth in demand with no DSM efforts. In talks with the EC responsible for the SNEP it was ascertained that the forecast electricity demand included non-explicit DSM considerations (EC, 2014).

The total installed capacity required in 2020 in the Reference Projection reaches approximately 3.7 times that reported in the SNEP. This discrepancy in generation requirements was due to a larger forecast of electricity demand along the planning horizon in the current work than that which was forecasted in the SNEP. Previous work has argued that the electricity demand forecasted in the SNEP was on the low side. Essah (2011) calculated electricity demand for Ghana in 2011, and found that a minimum installed capacity of 9,405.6 MW was required to meet this demand. The generation requirements found by Essah (2011) indicated a deficit in generation capacity of approximately 6,833 MW from the capacity requirements forecasted for 2011 in the SNEP from EC (2006a). [18]

It can be assumed that electricity demand will continue to grow, due to population growth, increased access to electricity, and economic development in Ghana. Economic growth in Ghana has exceeded the expectations that influenced the forecasted GDP along the SNEP planning horizon. The socio-economic development level forecast for 2020 in the SNEP was 1,875 US $/capita (EC, 2006a). Ghana, however, reported reaching 1,841 US $/capita in 2013 (GSS, 2014).

The possible underestimation of electricity demand may result in a gap between the actual demand and the installed generation (supply). This gap may also continue to grow wider as demand grows, while at the same time ageing and/or unmaintainable supply units are taken out of commission. This widening gap would mean that the installed electricity generation capacity was not able to meet electricity demand.

This possible gap between supply and demand may be evidenced by the power crises experienced by Ghana over 2014 and 2015. The national Electric Company of Ghana has been conducting rotational load shedding throughout the country due to electricity demand exceeding existing supply. The government has responded with stop gap efforts, establishing a new Ministry of Power to address the crises and ordering emergency power generation

[18] This calculated installed capacity requirement is based on demand and does not consider additional capacity requirements which would be necessary to ensure adequacy of electricity generation (due to loss of capacity from maintenance and repairs). Essah (2011) states that this may require and additional 20% installed capacity over that which was forecast, and therefore it is the minimum capacity (a conservative forecast). EC (2006a) forecasted generation requirements at 2,572 MW in 2011.

barges with a capacity of 1,000 MW to supplement generation capacity (Republic of Ghana, 2014; Kpodo, 2015).

Due to the differences in electricity demand in the Reference Projection of the current work and that forecast in the SNEP, the current work follows the shares of installed generation capacity types [%] reported in the SNEP, and not the actual installed capacity [MW] amount in 2008 or the forecasted years that were assumed in the SNEP of 2006 from EC (2006a). The total installed capacity assumed in the SNEP is shown together with the installed capacity modeled in the current work for the Reference Projection (2008-2020) in Figure 5-14.

The central supply alternative in the SNEP consisted of thermal (natural gas) and 10% renewables excluding hydro-electric generation EC (2006b) and reached 3,785 MW by the year 2020.

The Reference Projection followed the supply alternative of the SNEP and assumed that natural gas based generation technologies would remain the predominant installed capacity type followed by large hydro-electric generation. The electricity generation portfolio for the reference projection in the current work reaches 71% thermal, 21% hydro and 8% other renewables by the end of the planning horizon. The total installed capacity reaches 10,280 MW by 2020 as shown in Figure 5-14.

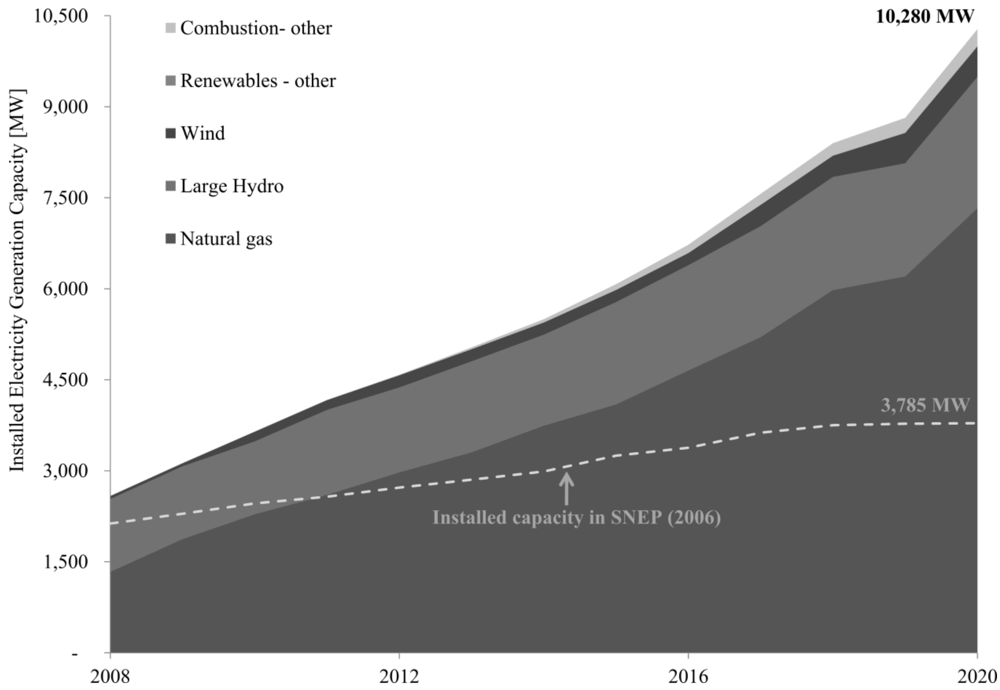

Figure 5-14 - Installed electricity generation capacity – Ghana reference projection

5.7.4.2 Minigrid

The minigrid electricity demand grew in proportion to new Rural household connections as detailed in Section 5.5 on energy access assumptions.

The required installed generation capacity was calculated based on the demand for electrical energy and the efficiencies of the generation technologies. Installed minigrid capacity consisted of hybrid solar PV and diesel generator systems, as described in Section 4.7.4.2.

The required installed capacity for the planning horizon reaches 1,055 MW in 2020, where 70% is solar PV and 30% is diesel generation capacity. The installed capacity for the reference projection is shown in Figure 5-15.

5.7.4.3 Standalone

The standalone systems electricity demand grew in proportion to new rural household connections as detailed in Section 5.5 on energy access assumptions.

The required installed generation capacity was calculated based on the demand for electrical energy and the efficiencies of the generation technologies. Installed standalone systems consisted solely of solar PV systems, as described in Section 4.7.4.3.

The required installed capacity for the planning horizon reaches 1,473 MW in 2020. The installed capacity is shown in Figure 5-16.

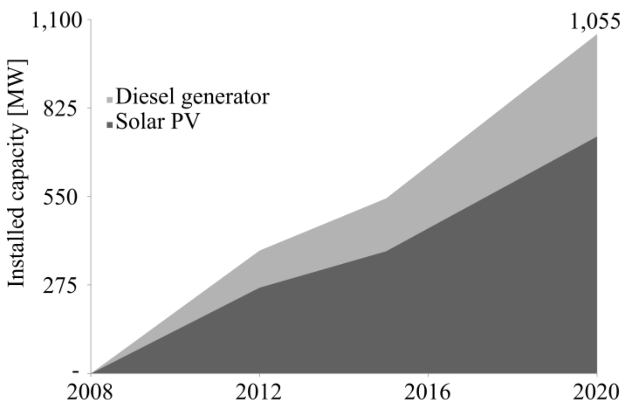

Figure 5-15 – Installed minigrid capacity – Ghana reference projection

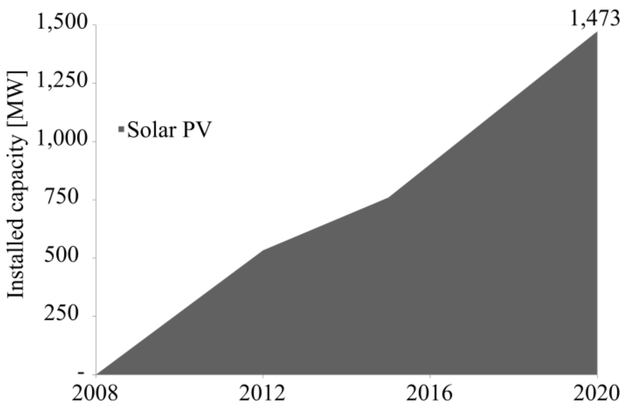

Figure 5-16 – Installed standalone systems capacity – Ghana reference projection

5.7.5 Transmission and distribution

The transmission and distribution system was considered within two dimensions. The first was the electrical energy losses attributable to the system. These losses were accounted for as a percentage of losses and were previously detailed in Section 4.7.5.2 on the national energy system model. The second dimension was the cost of transmission and distribution systems in which the two systems were considered in terms of the value [monetary units] of installed stock of transmission and distribution system lines [km].

Within the Reference Projection the losses accountable to the transmission and distribution systems remained unchanged, assuming that no specific interventions were made to decrease either technical or non-technical losses.

The installed stock [km] by line type for the base year 2008 is shown in Table 5-59. Here the total asset values [monetary unit (US $)] were aggregated into transmission lines and distribution lines.

Table 5-59 – Transmission and distribution system assets: Ghana 2008

Line type	Voltage level [kV]	Line [km]	Asset value [US $]
Transmission	161	4,000	5.63E+08
Sub-transmission	69	132	
Distribution 33kV	33	12,315	9.50E+08
Distribution 11kV	11	20,511	
Distribution 0.4kV	0.4	1,462,875	

References: (RCEEAR, 2005; ECG, 2008; Rosnes and Vennemo, 2009; PSEC and GRIDCo, 2010; EC, 2012c)

The total installed stock for the transmission and distribution system grew in proportion to FE demand or electricity provided by the national grid as described in Section 4.7.5.1 of the national energy system modeling Chapter 4. The annual growth rates relative to the base year are shown in Figure 5-17 for the reference projection. As the entire system was assumed to grow in proportion to the national FE demand, this growth rate was applicable to all system line types.

The resulting lengths of the system line types at the end of the planning horizon, 2020, are presented in Table 5-60.

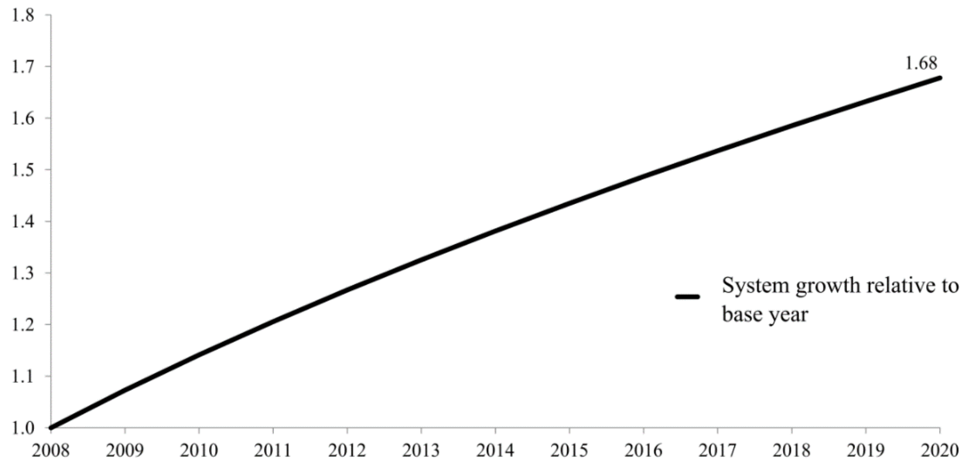

Figure 5-17 – Trans. and Dist. system growth relative to base year – Ghana reference projection

Table 5-60 – Trans. and Dist. system assets – Ghana reference projection 2020

Line type	Line [km] in 2020
Transmission	6,712
Sub-transmission	221
Distribution 33kV	20,665
Distribution 11kV	34,416
Distribution 0.4kV	2,454,600

5.8 Calibration of the energy system model for Ghana

The FE demand and the PE resource values from the energy demand and supply model were compared to the reported values in the SNEP from EC (2006e) for the corresponding base year of 2008.

It must be noted here that the values from the SNEP were not explicitly reported in all cases. When values were not explicitly reported, assumptions were required to extrapolate or to calculate from other data sets in the SNEP. When this was not possible placeholders were used until the modeling assumptions and preliminary data could be verified with energy sector actors in the case study. Therefore, the values referred to as "reported" were the explicit values or based on the best assumptions possible from reported information.

The modeled FE demand and the SNEP reported FE demand for the base year, 2008, are shown together in Figure 5-18. Here, the modeled FE demand is seen to be identical to those reported in the SNEP. No additional calibration was necessary due to the fact that the base year FE demand for the energy demand module of the energy system model was established through a disaggregation of the FE demand reported in the SNEP from EC (2006e). This process was described previously in Section 4.5.

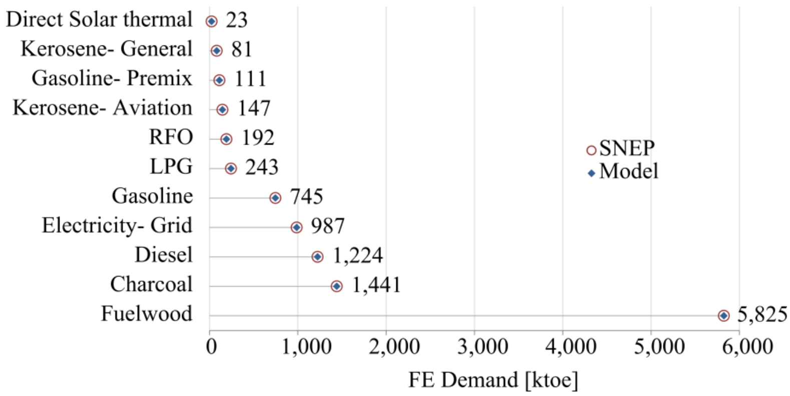

Figure 5-18 - FE demand calibration: Ghana 2008

The modeled PE resources and the SNEP reported PE resources for the base year, 2008, are shown in Figure 5-19. Due to assumptions made in the modeling of the PE resources and transformation module of the energy systems model, there were some discrepancies between the modeled and SNEP reported values.

The reported crude oil imports for the SNEP were higher than the modeled required resources. The crude oil requirements for 2008 were not explicitly cited, but extrapolated from values reported for 2004 and those that were forecast for 2020. This was an assumed value. This method was not ideal as it assumed a constant growth rate in the crude oil requirements for this period. Also, this method did not take into account possible changes in the operating capacity of the TOR which was the destination for imported petroleum. In the absence of more detailed data, however it was used as a placeholder.

The value from the model reflected the assumptions made for operation of the oil refinery, TOR see Section 4.7.3, based on the data available in the literature. The lower value in the model as opposed to the SNEP had repercussions in the values modeled and reported in the SNEP for imported petroleum products. Due to the lower crude oil imports and oil refinery production in the model, import requirements of kerosene, diesel, gasoline and RFO were larger than the SNEP reported values. Incongruities also existed in the PE resources for electricity generation due to assumptions in the electricity generation technology mix for the base year. Natural gas imports, indigenous hydro resources, and indigenous other renewables (i.e. small hydro, small wind, landfill gas, municipal solid waste, and woodwastes) were higher for the model than the values reported in the SNEP.

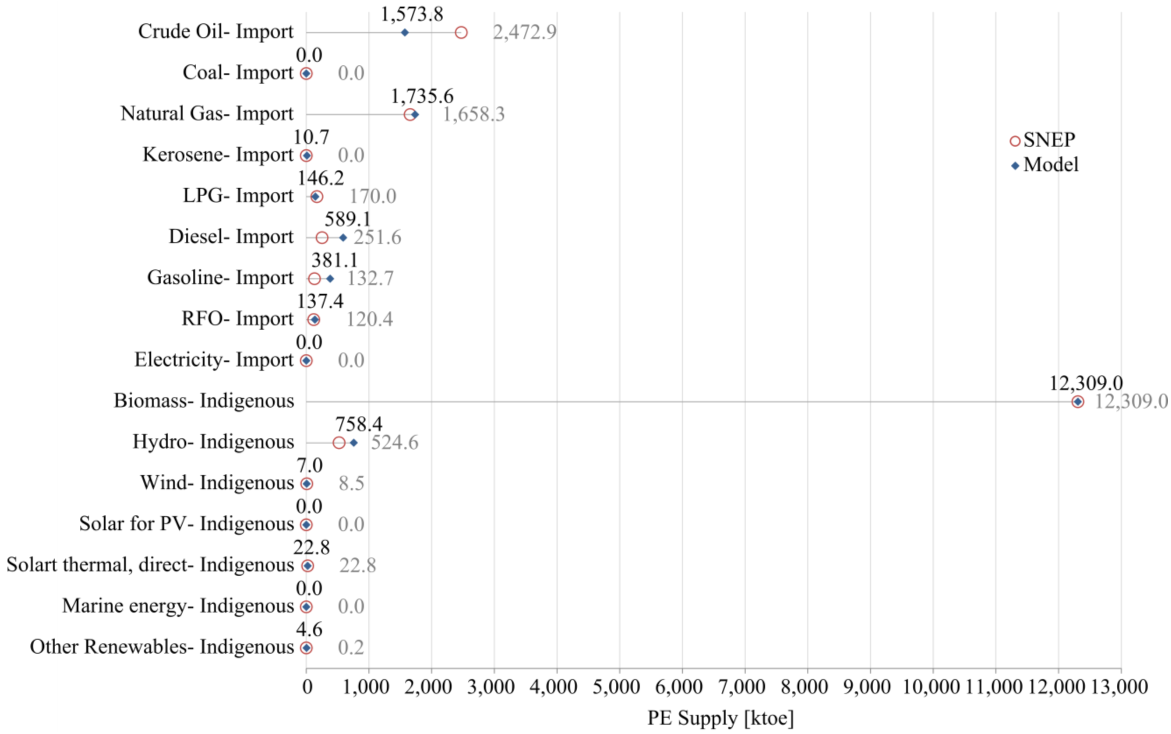

Figure 5-19 – PE supply calibration: Ghana 2008 [SNEP values are presented in grey to the right of the markers. Modeled values are presented in black above the markers]

5.9 Reference projection

The energy flows, representative of the FE demand and the PE supply and transformation for the base year 2008, are shown in Figure 5-20. The energy flows for the final year of the planning horizon, 2020, are shown in Figure 5-21. The PE imports representing 28% of net supply grew to 11,412 ktoe from 4,574 ktoe in 2008. Indigenous supply remained the largest share, 72%, increasing from 13,102 ktoe in 2008 to 29,522 ktoe.

Natural gas represented the largest share of PE imports. Crude oil imports were constrained to 2008 levels due to the petroleum refinery capacity. Petroleum product imports are seen to increase to supplement refinery output in meeting demand.

Biomass remained the dominant PE supply requirement for the national energy system. Supply requirements for biomass to meet fuelwood and charcoal production demand grew from 12,309 ktoe in 2008 to 27,678 ktoe in 2020.

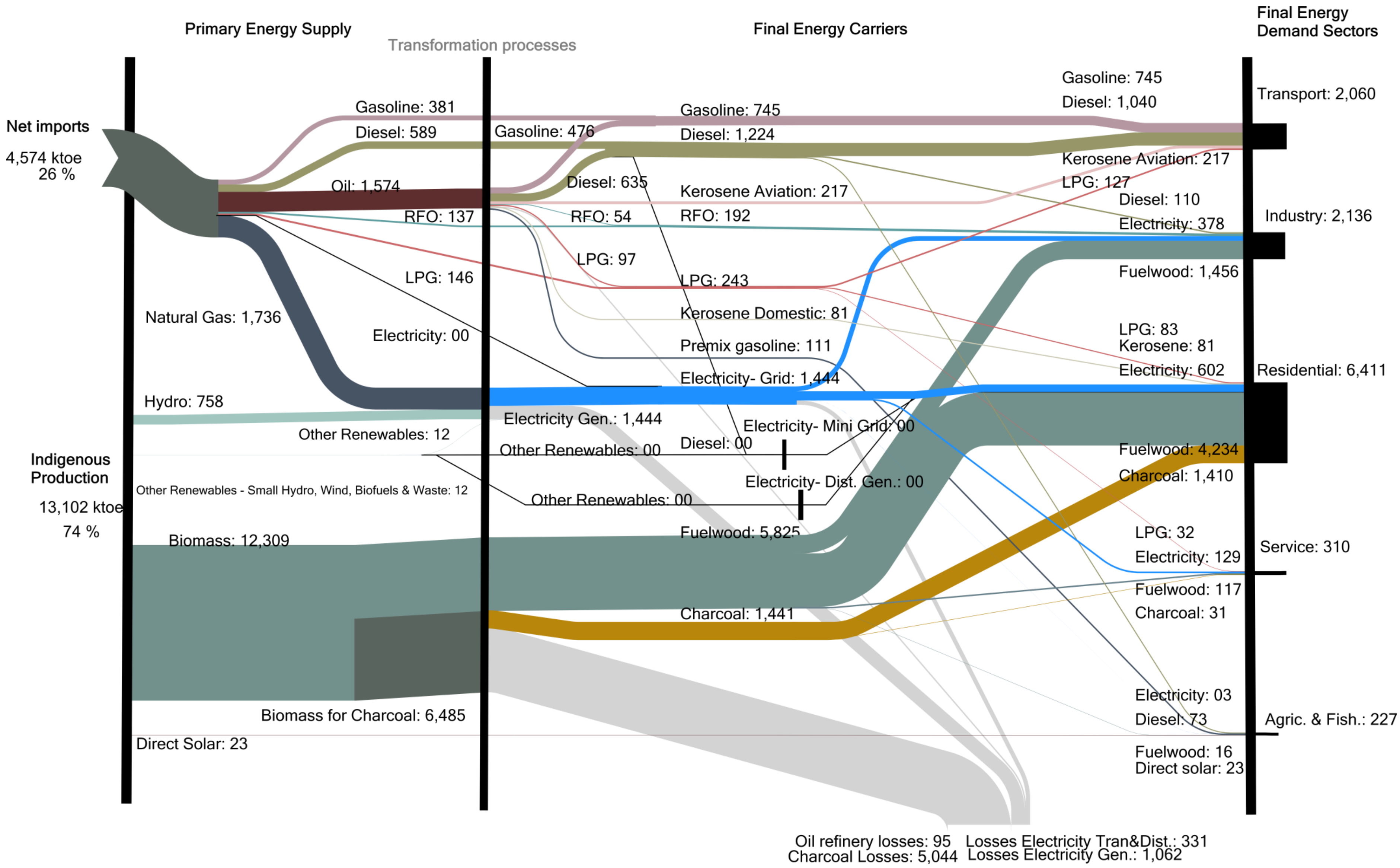

Figure 5-20 - Energy flow for Ghana 2008 [ktoe]

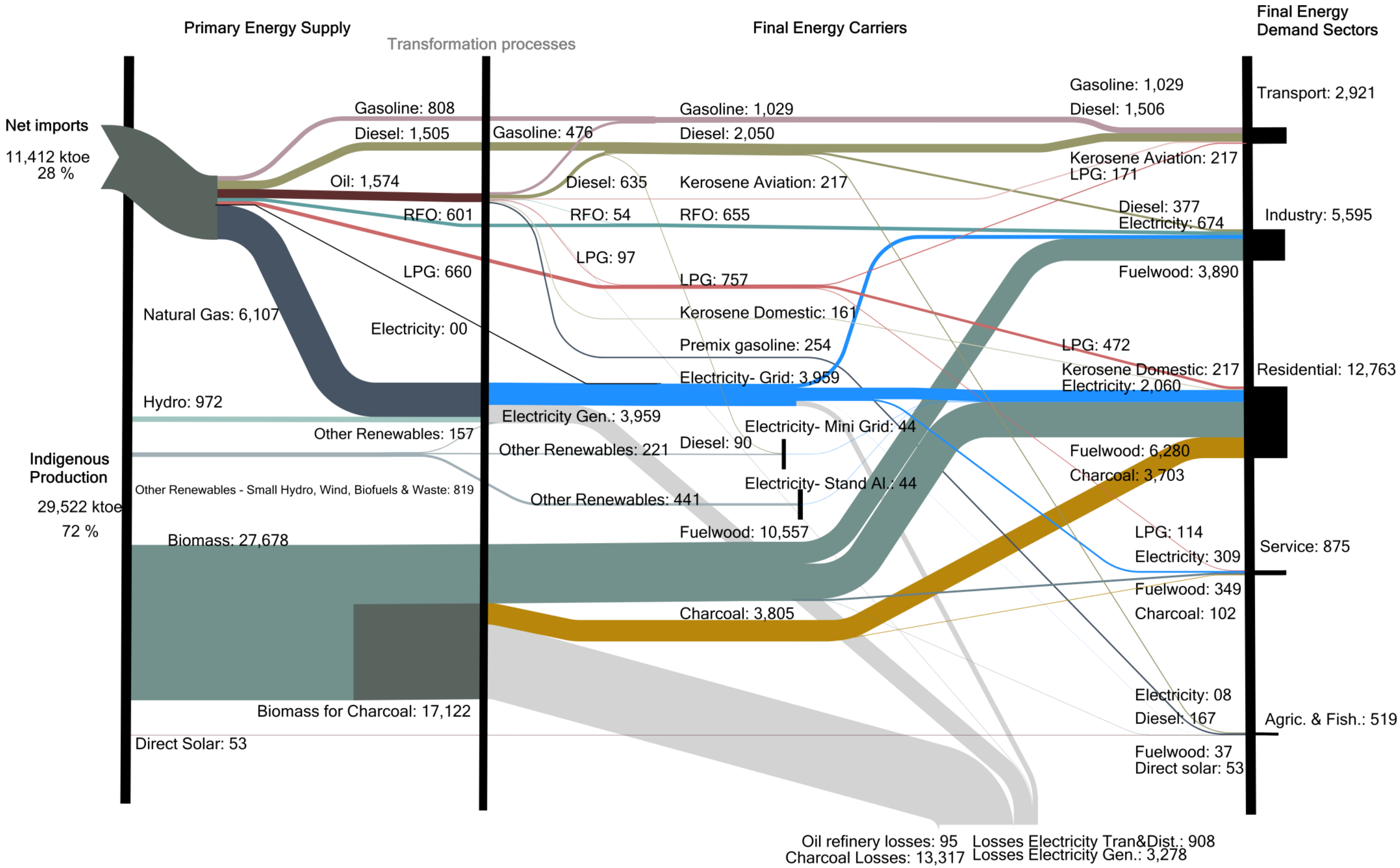

Figure 5-21 - Energy flow for Ghana 2020 - Reference projection [ktoe]

5.10 EP 2008-2020 alternatives

The third central activity of the EP methodology proposed in the current work, following (1st) Problem Structuring and (2nd) Energy Modeling, described in Section 3.2, was the Multi-Criteria Evaluation of a set of EP alternatives.

A set of EP alternatives was constructed for the eventual evaluation within the MCDA method selected for the current work, as described in Section 3.10.2. The set of EP alternatives were evaluated in their achievement of the EP objectives, which were presented in Section 3.5, through the use of the quantifiable attributes, detailed in Section 3.6. The evaluation activity is presented in Chapter 6.

A set of eight EP alternatives, for the 2008-2020 planning horizon, was developed for evaluation within the case study. The alternatives were constructed with the intention of expressing markedly contrasting options within the decision space of energy policy choices. This set of alternatives is presented in Table 5-61 with brief narratives of the energy policies and actions that the alternative was constructed to model.

Each constructed EP alternative, in the context of the MCDA model as described in Section 3.8, represented a set of actions, constructed by the modeler, which resulted in a future reflecting different outcomes as compared to the Reference Projection (Finnveden et al., 2003). The descriptions that follow present the set of actions that were followed in the alternative and the situation in 2020. A summary of the divergences of the EP alternatives, from the Reference Projection, for the final year of the planning horizon, 2020, is shown in Table 5-62. Additional details about the alternatives for the planning horizon are presented in Appendix C.

Table 5-61 – Energy planning alternatives: Ghana case study

Alternative		Brief narrative of the alternative
1	PRVREN Proven renewables	Consists of a set of actions that promote more the use of renewable electricity generation technologies for the main grid which have been *proven* in the context of Ghana and/or West Africa. Technologies that have *proven* examples represent maintainable options due to experience in installation, operation and maintenance.
2	YNGREN Young renewables	Describes a set of actions that consist of increased capacity from renewable electricity generation technology unproven in the context of Ghana and or West Africa. These renewable technologies do not have installed examples in Ghana or West Africa and are considered *young* in terms of experience in installation, operation and maintenance.
3	MNIGRD Access minigrid	Describes a set of actions that closely follow that of the reference projection. However, policies favor more local mini-grids over central grid expansion to reach access targets for electricity.
4	STDALN Access standalone	Presents a set of actions that again follow that of the reference projection. However, policies favor more the use of standalone generation technologies at the household level over grid connections to reach electricity access targets.
5	DSMREF DSM & Refinery	Consists of a set of actions that increase the capacity for production of petroleum based fuels from the TOR for domestic use. The electricity generation portfolio plan follows that of the reference projection installing primarily thermal generation technologies, however due to DSM efforts in the residential and Service sectors electricity demand is decreased for the planning horizon.
6	DIVRSI Diverse actions I	Describes a set of actions that promote DSM efforts, installation of proven renewables in the electricity generation portfolio, access to minigrids for rural populations and increased refinery capacity.
7	DIVRSII Diverse actions II	Presents a set of actions that build upon the DIVSI Alternative with DSM efforts, installation of proven renewables in the electricity generation portfolio, access to minigrids for rural populations and increased refinery capacity. The current alternative also includes a shift in road passenger and freight transport to rail following the completion of the "Western Railway Project" in 2008.
8	DIVRSIII Diverse actions III	Consists of a set of actions that build upon the DIVSI Alternative with DSM efforts, installation of proven renewables in the electricity generation portfolio, access to national grid for rural populations and increased refinery capacity. Achievement of the goal of 100% electricity access is delayed resulting in a share of 90% of the population with access at the end of the planning horizon.

5.10.1 Alt. 1 - Proven renewables

The Proven Renewables alternative consists of policies that promote the use of renewable electricity generation technologies for the main grid which have been proven in the context of Ghana and or West Africa. Technologies that have proven examples represent maintainable options due to experience in installation, operation and maintenance. The constructed alternative is presented below through a description of the main assumptions made.

Electricity Access: New connections for all population types followed the majority grid connection access strategy of the Reference Projection. Within the Reference Projection new Rural grid connections to the main grid, minigrids, and standalone systems were assumed to be 80%, 10% and 10% respectively.

Energy Demand: Assumptions followed those of the Reference Projection as described in Section 5.6.

Electricity Generation: As in the Reference Projection electricity generation was provided by predominantly thermal generation consisting of gas turbines and combined-cycle gas turbines. Renewable generation technologies, excluding large hydro, comprising the capacity expansion plan were those that were considered proven in the context of application. This consists of onshore wind and PV technologies.

The generation capacity, assumed for the current alternative, consisted of 54% thermal (Gas turbine (GT) and Combined Cycle GT (CCGT), 20% large hydro, 26% wind (onshore), and a residual amount of other renewables 0.3% (landfill gas, municipal solid waste, & wood waste). The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

5.10.2 Alt. 2 - Young renewables

The Young Renewables alternative describes a pathway that consists of increased capacity from renewable electricity generation technology unproven in the context of Ghana and or West Africa. These renewable technologies do not have installed examples in Ghana or West Africa and are considered "young" in terms of experience in installation, operation and maintenance. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: Followed the Reference Projection.

Electricity Generation: The largest share of installed capacity is thermal generation consisting of gas turbines and combined-cycle gas turbines. Renewable generation technologies, excluding large hydro, were those considered to be less proven or "young" entries to the context of application. This consisted of offshore wind, large PV plant, concentrated solar, wave, solar, landfill gas, municipal solid waste, and wood waste technologies.

The generation capacity, assumed for the current alternative, consisted of 48% thermal (GT and CCGT), 21% large hydro, 17% wind (onshore & offshore), 12% other renewables (small wind and hydro, PV, concentrated solar, wave, tidal) and 2% other combustion (landfill gas, municipal solid wastes, & wood wastes). The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

5.10.3 Alt. 3 – Minigrid Access

The Minigrid Access alternative describes a trajectory that closely follows that of the Reference Projection; however, policies favor local mini-grids over central grid expansion to reach access targets for electricity. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for rural populations consisted of 20% grid, 70% minigrid, and 10% standalone. New connections for Core-Urban and Peri-Urban populations remain 100% main grid connections.

Energy Demand: Followed the Reference Projection.

Electricity Generation: Due the shift in new rural connections from the grid to local minigrids the Minigrid Access alternative presented a decreased demand from the grid resulting in lower installed capacity requirements for grid generation during the planning horizon.

The generation capacity, assumed for the current alternative, consisted of 70% thermal (GT and CCGT), 24% large hydro, 4% wind (onshore), and 2% other combustion (landfill gas, municipal solid wastes, & wood wastes). The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

5.10.4 Alt. 4 - Standalone Access

The Standalone Tech Access alternative describes a pathway that again follows to a great degree that of the Reference Projection, however policies favor the use of standalone generation technologies at the household level over grid connections to reach electricity access targets. The constructed alternative is presented below through a description of the main assumptions made.

Electricity Access: New connections for rural populations consisted of 20% grid, 10% minigrid, and 70% standalone. New connections for Core-Urban and Peri-Urban populations remain 100% main grid connections.

Energy Demand: Followed the Reference Projection.

Electricity Generation: Resulting from the preference for standalone technologies opposed to the grid for new connections the current alternative presented a decreased demand from the grid resulting in lower installed capacity requirements for grid generation during the planning horizon. The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

The grid electricity generation expansion plan, assumed for the current alternative, followed that of the Minigrid Access alternative previously described.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

5.10.5 Alt. 5 - Refinery & DSM

The DSM and Refinery Capacity alternative consisted of activities that increase the capacity for production of petroleum based fuels from the TOR for domestic use. The electricity generation portfolio plan follows that of the Reference Projection installing primarily thermal generation technologies. However due to DSM efforts in the Residential and Service sectors, electricity demand was decreased for the planning horizon requiring less installed capacity. The constructed alternative is presented below through a description of the main assumptions made.

Electricity Access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: DSM activities within the Residential and Service sectors reduced the peak demand.

The DSM considerations in the current alternative consisted of energy conservation efforts restricted to FE demand for electricity. Energy conservation efforts have the goal of reducing energy demand through efficient use of energy and can be achieved through increased use of efficient appliances as well as changes in lifestyle (Bhattacharyya, 2011). Lifestyle changes were considered outside the scope of the current work and so interventions were solely made through shifts to efficient end-use conversion electrical appliances.

As stated in Section 1.1.1, and highlighted in the Figure 1-1, increased energy consumption is closely linked to economic development. From this the justification for DSM efforts in the setting of Ghana, a developing country, may not be apparent. The efforts to conserve energy in the context of Ghana were not made to limit the provision of FE services within the demand sectors, but to ensure that FE was used efficiently. The FE demand for electricity is increasing both due to increased output from the productive sectors, increased affluence of populations (reflected in household ownership of appliances), and increased access to electricity. This additional FE demand requires new infrastructure as well as additional PE supply to meet demand. The efficient use of energy on the demand side results in attractive corollaries on the supply and transformation side of the energy balance. This is seen in the example that 1 MWh of energy savings results in a savings of more than 1 MWh of electricity generated due to system losses. As a consequence electricity system expansion requirements are lessened and results in lower additional infrastructure costs, PE supply, and corresponding environmental impacts (Bhattacharyya, 2011).

Energy conservation efforts in the current alternative were limited to interventions are made in the Residential and Service sectors through shifts in the end-use mix of appliances to more efficient alternatives. Additional future efforts could also be made for DSM efforts in the Industry sector.

The Residential sector represented the largest FE demand for electricity through the planning horizon in the Reference Projection. The share that the Service sector represents of GDP was forecast to grow in the planning horizon, and the FE demand for the sector could be expected to grow accordingly. These are described briefly below, and presented in more detail in the Appendix C.

In the Residential and Service sectors interventions consisted of shifts:

- To more efficient Fluorescent lamp and ballast systems (T8 & T5 w/electronic ballasts).
- From Incandescent bulbs to 17% CFL & 17% LED lighting in 2020.
- Away from emersion & kettle water heaters to a mix of insulated storage heaters.
- To solar thermal water heaters from 2% in 2008 to 14% in 2020.
- To efficient combined refrigerator + freezer units by 2020.
- To efficient freezer units by 2020.
- To more efficient (higher EER) AC units.
- To efficient washing machines and dishwashers by 2020.
- To improved fuelwood and charcoal cookstoves for cooking and water heating

All remaining FE demand follows the Reference Projection.

Electricity Generation: Electricity demand was decreased in the current alternative resulting from the DSM efforts and in turn capacity expansion requirements were lower than those of the Reference Projection.

The generation capacity, assumed for the current alternative, consisted of 70% thermal (GT and CCGT), 21% large hydro, 6% wind (onshore), 3% other combustion (landfill gas, municipal solid wastes, & wood wastes) and a residual share of other renewables 0.1% (small wind and hydro). The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: The TOR operating capacity was increased following the options described in EC (2006c) for the addition of a "reformer or isomerization unit" and a "cracker. The total refining capacity increased from 29,736 barrels per day (b/d) to 99,736 b/d in 2020 respectively with this expansion. The operating capacity is shown in Figure 5-22.

This increased capacity resulted in additional crude oil imports for domestic production of petroleum based fuels.

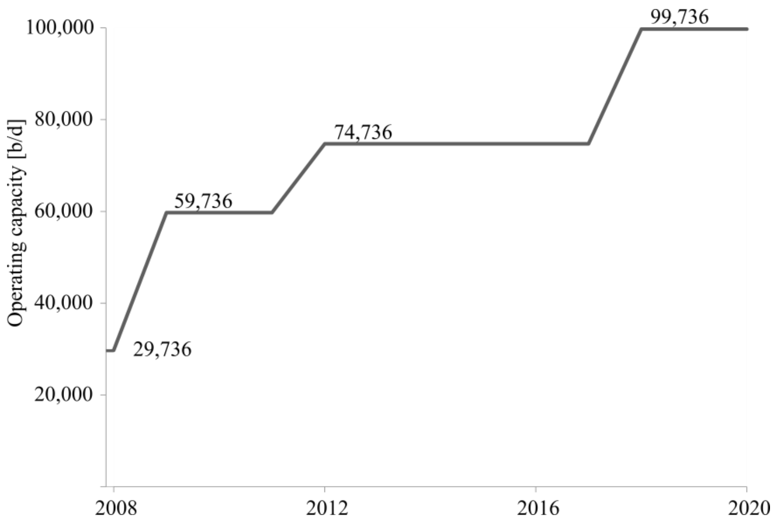

Figure 5-22 - TOR operating capacity: Ghana Alt. 5 Refinery & DSM

Transportation: Follows the Reference Projection.

5.10.6 Alt. 6 - Diverse actions I

The Diverse Actions I alternative consists of a mix of policies that promote DSM efforts, installation of proven renewables in the electricity generation portfolio, access to minigrids for rural populations and increased refinery capacity. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for rural populations consisted of 20% grid, 70% minigrid, and 10% standalone. New connections for Core-Urban and Peri-Urban populations remained 100% main grid connections.

Energy Demand: DSM activities within the Residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

All remaining FE demand followed the Reference Projection.

Electricity Generation: Electricity demand was decreased in the current alternative resulting from the DSM efforts and in turn capacity expansion requirements are lower than those of the Reference Projection.

As in the Reference projection, electricity generation was provided by predominantly thermal generation consisting of gas turbines and combined-cycle gas turbines. Renewable generation technologies comprising the capacity expansion plan were those that were considered proven in the context of application.

The generation capacity, assumed for the current alternative, consisted of 50.8% thermal (GT and CCGT), 25.4% large hydro, 23.4% wind (onshore), and a residual share of other renewables 0.4% (small wind and hydro). The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Increased oil refinery capacity followed the policy interventions as described in the DSM and Refinery Capacity Alternative described separately.

Transportation: Followed the Reference Projection.

5.10.7 Alt. 7 - Diverse actions II

The Diverse Actions II alternative presents of a mix of policies building upon the Diverse Actions 1 Alternative with DSM efforts, installation of proven renewables in the electricity generation portfolio, access to minigrids for rural populations and increased refinery capacity. The current alternative also included a shift in road passenger and freight transport to rail following the completion of the "Western Railway Project" assumed to be completed in 2008. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for rural populations consisted of 20% grid, 70% minigrid, and 10% standalone. New connections for Core-Urban and Peri-Urban populations remain 100% main grid connections.

Energy Demand: DSM activities within the Residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

All remaining FE demand followed the Reference Projection.

Electricity Generation: The electricity generation capacity expansion, assumed for the current alternative, followed that of the Diverse Actions 1 alternative. The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Increased oil refinery capacity followed the policy interventions as described in the DSM and Refinery Capacity Alternative described separately.

Transportation: With the completion of the "Western Railway Project" it was assumed that policy efforts would promote a shift in passenger and freight transport towards rail transport. The shift included both collective and private road transport of all fuel types as well as freight transport of all categories, e.g. medium and heavy, and fuel types. By 2020 10% of private and collective passenger transport, 5% of passenger taxi transport, and 20% of freight transport were assumed to shift to collective and freight rail transport. This is further detailed in details of Alt. 7 DIVRSII of Appendix C

The annual shift of mobility from road transport to rail transport was assumed to be relatively small in proportion to total mobility. This was due to the region of Ghana that the "Western Railway Project" was planned to serve, and the low share of mobility that the rail sub-sector represented. The "Western Railway Project" was planned to first renew the rail lines from Takoradi on the south-western coast to Kumasi in the central region. The second stage of the project was planned to continue this line to the village of Hamile located north of Wa, a town on the north-western boarder of Ghana with Burkina Faso. Please refer to the map in Figure 5-1 in Section 5.3.

5.10.8 Alt. 8 - Diverse actions III

The Diverse Actions III alternative consists of a mix of actions building upon the Diverse Actions 1 Alternative with DSM efforts, installation of proven renewables in the electricity generation portfolio, access to minigrids for rural populations and increased refinery capacity. Achievement of the goal of 100% electricity access was delayed resulting in a share of 90% of the population with access at the end of the planning horizon. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: The assumptions for access in the current alternative set the goal for universal electricity access at 2030 instead of 2020. Therefore, the current alternative assumed that the electricity access rate is delayed in comparison to the Reference Projection. The share of population that would receive access to electricity reaches 90% by 2020. This corresponds to a share of 94%, 94% and 79% for CoreUrban, PeriUrban and Rural population households respectively. New electricity connections for rural populations are predominantly to the main grid following the assumptions for the Reference Projection. New connections for Core-Urban and Peri-Urban populations remained 100% main grid connections.

Energy Demand: DSM activities within the Residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

All remaining FE demand followed the Reference Projection.

Electricity Generation: The electricity generation capacity expansion, assumed for the current alternative, followed that of the Diverse Actions 1 alternative. The share of installed capacity by generation technology is shown in Table 5-62. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Increased oil refinery capacity followed the policy interventions as described in the Reference Projection.

Transportation: Followed the Reference Projection.

5.10.9 Summary of EP 2008-2020 alternatives

The current section described the assumptions made for the set of eight EP alternatives for the 2008-2020 planning horizon. These EP alternatives were to be evaluated in their achievement of the EP objectives, detailed in Section 3.5 and 3.6, over that of the Reference Projection, detailed from Section 5.5 to 5.7. For this reason, the differences between the alternatives and the Reference Projection over the planning horizon were of specific interest here. A summary of how the EP alternatives presented in the current section diverge from the Reference Projection in the year 2020 is presented in Table 5-62.

Table 5-62 - Summary of divergence of EP alternatives from the Reference Projection - Ghana 2020

FE Access & Demand Projection for 2020	Reference Projection	Alt. 1 PRVREN[1]	Alt. 2 YNGREN	Alt. 3 MNIGRD	Alt. 4 STDALN	Alt. 5 DSMREF	Alt. 6 DIVRSI	Alt. 7 DIVRSII	Alt. 8 DIVRSIII
Access rates[2] [%]									
Fuelwood	100 100 100								
Charcoal	80 80 76								
Kerosene	100 90 80								
LPG	53 33 5								
Electricity	100 100 100								94 94 79
Total FE demand [ktoe]									
Direct solar thermal	52.7								
Fuelwood	10,556.5					7,718.9	7,718.9	7,718.9	7,718.9
Charcoal	3,804.8					3,026.4	3,026.4	3,026.4	3,026.4
Kerosene – General use	161.0								
LPG	757.1								
Electricity – Grid[3]	3,050.4			2,785.7	2,785.7	2,457.1	2,262.8	2,262.8	2,342.4
[GWh]	35,469.9 GWh			32,391.5 GWh	32,391.5 GWh	28,496.3 GWh	26,312.0 GWh	26,312.0 GWh	26,312.0 GWh
Electricity– MiniGrid	44.1			308.9	44.1	32.4	226.6	226.6	22.7
[GWh]	513.1 GWh			3,591.5 GWh	513.1 GWh	376.5 GWh	2,635.3 GWh	2,635.3 GWh	363.5 GWh
Electricity– Standalone	44.1			44.1	308.9	32.4	32.3	32.3	22.7
[GWh]	513.1 GWh			513.1 GWh	3,591.5 GWh	376.5 GWh	375.1 GWh	375.1 GWh	363.5 GWh
Diesel	2,049.9							2,011.9	
Gasoline	1,029.2							1,023.0	
Gasoline– Premix	253.9								
Kerosene– Aviation	214.3								
RFO	655.1								

1. The values presented for the EP 2008-2020 alternatives consist only of those that diverge from those of the Reference Projection.
2. Access rates for the FE carriers refer to the Residential demand sector are presented in the order [CoreUrban PeriUrban Rural] within the respective column.
3. Electricity demand does not include Transmission and distribution losses.

Table 5-62 Continued

PE Supply Projection for 2020	Reference Projection	Alt. 1 PRVREN	Alt. 2 YNGREN	Alt. 3 MNIGRD	Alt. 4 STDALN	Alt. 5 DSMREF	Alt. 6 DIVRSI	Alt. 7 DIVRSII	Alt. 8 DIVRSIII
Share in PE Supply [%]									
Imports	28	27	24	27	25	31	29	29	29
Indigenous	72	73	76	73	75	69	71	71	71
PE Supply Import [ktoe]									
Crude oil	1,573.8					4,136.9	4,136.9	4,130.3	
Coal	0.0								
Natural gas	6,107.0	5,443.8	4,317.9	5,551.2	5,551.2	5,017.4	3,898.7	3,898.7	4,035.8
Kerosene	157.9					0.0	0.0	0.0	
LPG	660.3					482.5	482.5	482.5	
Diesel	1,505.0			2,045.1		315.3	711.6	673.5	1,461.2
Gasoline	807.5					0.0	0.0	0.0	
RFO	600.9					501.5	501.5	501.5	
Electricity	0.0								
PE Supply Indigenous Resources [ktoe]									
Biomass	27,678.1					21,337.5	21,337.5	21,337.5	21,337.5
Hydro	972.3	1,078.1	1,286.7	943.9	943.9	809.0	999.6	999.6	1,034.7
Wind	49.8	256.0	196.1	34.4	34.4	48.2	203.8	203.8	211.0
Solar – for PV	661.9	665.7	784.3	1,985.6	3,309.3	485.6	1,461.2	1,461.2	344.3
Solar thermal	52.7								
Marine energy	0.0		352.0						
Other Renewables[4]	107.3	4.0	104.0	65.0	65.0	103.7	3.7	3.7	3.8
Transformation - Indigenous Production [ktoe]									
Kerosene –TOR[5]	217.4					375.3	375.3	375.3	
LPG-TOR	96.8					274.6	274.6	274.6	
Diesel-TOR	634.9					1,800.7	1,800.7	1,800.7	
Gasoline-TOR	475.5					1,283.1	1,283.1	1,276.9	
RFO-TOR	54.2					153.6	153.6	153.6	
Transformation - Installed capacity – Grid Electricity generation shares [%]									
Natural gas	71.3	54.2	48.3	69.5	69.5	69.5	50.8	50.8	50.8
Coal	0.0								
Large hydro	21.0	20.0	21.2	24.5	24.5	21.4	25.4	25.4	25.4
Wind	4.9	25.5	17.0	4.0	4.0	5.8	23.4	23.4	23.4
Marine	0.0		6.8						
Renewables – other[6]	0.1	0.3	4.8	0.1	0.1	0.1	0.4	0.4	0.4
Combustion – other[7]	2.7	0.0	1.9	1.9	1.9	3.2	0.0	0.0	0.0

4. Comprises small hydro, small wind, landfill gas, municipal solid waste, and woodwastes.
5. TOR refers to petroleum based products produced domestically from the Tema Oil Refinery.
6. Small hydro, wind and PV
7. Landfill gas, municipal solid waste and woodwastes

Chapter 6

Case study part II - Multi-criteria evaluation

Application of national energy planning methodology

6.1 Introduction to the case study part II

In Chapter 5, Part I of the case study, the choice of the country of application, Ghana, was discussed. A depiction of Ghana was made in the context of the current work, and the energy sector of Ghana was described. The energy model detailed in Chapter 4 was applied to modeling the national energy system of Ghana to develop a Reference Projection. Finally, a set of EP alternatives was established that represented potential energy policy paths.

The current chapter is a continuation of the application of the national EP methodology. In the current installment of the case study, the decision support methodology described in Chapter 3 is applied, and the EP alternatives constructed in Chapter 5 are evaluated to answer the third, and final, research question of the work[19]:

> *How do the results from an EP methodology including these additional objectives differ from those from a methodology including solely the base objectives?*

6.2 Evaluation

The national EP methodology developed for the current work and detailed in Chapter 3 consists of three central activities. These were the (1) problem structuring, (2) energy modeling, and (3) MCDA evaluation activities.

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[19] The set of three research questions for the current work were presented in Subchapter 1.2.

The current chapter will follow the methods that were chosen in Section 3.10 for the MCDA evaluation activity. This begins with a description of the DC held with DMs for the evaluation of the EP alternatives. Next, the results of the evaluation of the alternatives with the MCDA models selected for this work are presented. This is done within the framework of all three EP objective sets (i.e. ECOWAS+, ECOWAS, and Developed Countries). An expanded set of EP alternatives is presented and evaluated. Finally, a sensitivity analysis is presented to evaluate how the results may differ given variations in the performances of alternatives.

6.3 Decision conference

The DC held at the Energy Commission of Ghana in Accra on January 27, 2015 was conducted for the purpose of evaluating national EP alternatives for Ghana. The goal of the DC was to support future policy development activities in Ghana. The strategic objectives for the DC are outlined below.

The specific objectives of the conference are:

1. To gather key experts and stakeholders who are interested in EP in Ghana.
2. To review EP alternatives and discuss what EP objectives they should be expected to achieve.
3. To assess the level to which each EP alternative achieves the chosen objectives through corresponding quantifiable attributes.
4. To discuss possible trade-offs between the EP objectives.
5. To identify the most interesting EP alternatives based on the preference information provided by the group of participants.

Invitations were extended to participants through the DC host institution, The Energy Commission of Ghana. The invited institutions and the corresponding representatives in attendance are presented in Table 6-1.

Table 6-1 - Decision Conference - Invited and attending participants: Case Study

Name of Institution invited	Stakeholder type	Representatives in attendance
Ministry of Power	Government	2
Energy Commission Ghana (EC)	Government	8
Institute of Statistical, Social and Economic Research	Research Institute	1
Centre for Scientific and Industrial Research	Research Institute	0
Ghana Academy of Arts and Sciences	Research Institute	0
Kumasi Institute of Technology and Environment (KITE)	NGO, Interest Group & Research Institute	0
The Energy Center (TEC), Kumasi	Research Institute	6[1]

1. Estimated based on conversations with colleagues in attendance as TEC attended via 1-way video conference which was interrupted during the DC.

The DC began with a description of the current work and the purpose of the conference. This was followed by an effort to frame the EP problem in the context of developing countries in which Ghana was used as a point of departure.

The DC program is presented here to outline the description of the activities conducted.

The DC Program:

1. Introduce the facilitator(s) and participating actors as well as the EP case study of Ghana.
2. Present the reviewed EP objectives and corresponding attributes chosen to evaluate alternatives in Sections 3.5 and 3.6, and receive constructive feedback.
3. Review the reference projection, Sections 5.4 to 5.7, and the pre-constructed EP alternatives, Section 5.10, to be evaluated. Present the performance of each of the EP alternatives on the attributes.
4. Develop value functions for the individual attributes allowing the performance of the alternatives to be translated into comparable values. Establish an ordinal ranking of importance parameters.
5. Explore the types of preference choices that could lead to the choice of different alternatives in the absence of preference information. (JSMAA software)
6. Evaluate the global value of each of the EP alternatives as well as the value differences that exist between each of the alternatives given some preference information. (VIP Analysis software)

6.3.1 Framing the problem

Framing of the problem at the DC began by posing the following question to the participants:

What objectives can be identified for national energy planning activities in Ghana?

In response to this question the participants provided EP objectives as well as justification for them.

The discussion that this initiated allowed participants to explore the reasons for which EP in Ghana may be conducted and each other's preferences. In addition, the discussion permitted the facilitator to introduce the concepts of *fundamental* objectives, *means* objectives and ends objectives, discussed previously in Section 3.5, in response to a discussion of the proposed objective "*maximize renewables in the energy system*" which was agreed upon to be a *means* objective to either "*maximize PE security*" or "*minimize the impacts of the energy system on the global and/or local environment.*"

Overall the EP objectives that the participants suggested resembled those within the ECOWAS+ set. The participants suggested 12 objectives for EP in Ghana.[20] Of these, nine were EP objectives, two dealt with overall implementability and sustainability of planning, and one was specific to regulatory issues outside the scope of the current work. All nine of the EP objectives proposed were already addressed within the proposed ECOWAS+ objective set (detailed in Section 3.4). The proposed objectives and a discussion of how they relate to the ECOWAS+ objective set are presented below.

The participants stated objectives regarding "*Access to energy*", "*Minimized reliance on woodfuels*", and "*Ensuring the productive use of energy*". These three concerns were addressed in the ECOWAS+ objective to *Maximize population with access to FE* (Section 3.6.4.1). The participants identified "*Maximize PE security*" as a potential EP objective as well as "*Increase the share of renewables*". These objectives were both addressed in the ECOWAS+ objective to *Maximize PE security* (Section 3.6.1) and/or the objective to *Minimize the influence of energy use on the global climate* (Section 3.6.6). Participants cited the objective to "*Ensure the reliability of the energy system*", which was addressed by the ECOWAS+ objective to *Maximize the reliability of the FE supply* (Section 3.6.2). Participants identified the EP objective to "*Minimize local environmental impacts*" which was addressed by the ECOWAS+ objective to *Minimize the impacts on the local environmental impact* (Section 3.6.7). Participants cited the objective to "*Ensure the affordability of energy*" which was a concern addressed by the ECOWAS+ EP objective to *Minimize the costs of the energy system* (Section 3.6.5). The participants cited the objective to "*Improve energy efficiency at both the supply and demand side*". The *end* objective of this cited *means* objective was not immediately clear, as it may address concerns for PE security, Environmental impacts (global and local), FE system costs, and/or affordability of FE for the population. It was assumed that the multiple concerns that this objective may represent were addressed by the set of ECOWAS+ objectives.

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[20] The EP objectives suggested by the participants were not all *ends* objectives or stated in terms of *minimize* or *maximize*. The EP objectives proposed comprised: "increased access to electricity (stated as a target of 100%)", "increase the share of renewables energy (as stated)", "maximize PE security", "reduce CO_2 emissions (stated as important now due to international financial support which is potentially attached)", "sustainable development (stated as choosing energy options which are financially attractive, indigenously available, and socially acceptable)", "minimize local environmental impacts", "minimize reliance of woodfuels", "ensure affordability of energy for the population", "ensure the productive use of energy (emphasis on rural communities showing that electricity will be used for productive uses)", "improve energy efficiency at both the supply and the demand side", "ensure the reliability of the energy system (stated that infrastructure is important for this)", "reduce implementation weaknesses (ensure implementation of plans – referred to the SNEP (2006) which was developed but not implemented by the government)", "ensure the 'liberalization' of the energy system (stated for allowing private enterprises into petroleum extraction and electricity generation)".

The participants identified the objective to "*reduce implementation weaknesses of plans*", which was not an explicitly identified ECOWAS+ EP objective. However, the objectives of this set were identified to support implementable and sustainable EP activities (Detailed in the Section 1.2 – Research Objectives and Section 3.4- Framing the problem). The participants also identified "*Sustainable development*" as an objective. Participants clarified that the word "sustainable" referred to plans that were "financially attractive", used "indigenously available resources", and were "socially acceptable". The concern for "*financially attractive*" energy systems was included in the ECOWAS+ objective to Minimize costs of the energy system (Section 3.6.5). The objective to "*use indigenously available resources*" was a concern which was included in the ECOWAS+ objective to *Maximize PE security* (Section 3.6.1). The objective to be "*socially acceptable*" may include many concerns; however, it was assumed that it includes considerations of access to modern energy, reliability of FE supply, local environmental impact, and the costs related to the energy system. The concerns expressed in these objectives were already considered within the ECOWAS+ objective set.

An additional objective cited by the participants, to "*ensure the liberalization of the energy system*" dealt expressly with regulatory issues that were not within the scope of the current work.

Following this discussion, the *proposed* set of seven ECOWAS+ EP objectives and corresponding attributes were presented to participants, as presented previously in Section 3.5. Confirmation was obtained that the *proposed* ECOWAS+ set was appropriate for the conduction of the EP event. In addition, the participants agreed that, if there was interest, a new set of EP objectives and attributes could be identified and used for evaluation of the alternatives, at an appropriate time following the DC.

Due to time constraints and the DC program, it was not possible to incorporate additional EP objectives and quantifiable attributes into the framework of evaluation used at the DC. Assessing the performance and value scoring of alternatives

The EP alternatives, as well as the Reference Projection, were evaluated in achievement of the ECOWAS+ EP objectives prior to the DC, following the quantifiable attributes detailed in Section 3.6. The performance matrix detailing their performance, on these attributes, was constructed and is presented in Table 6-2.

Mutual independence requires that the performance of the alternatives on any attribute can be assessed and values assigned (including preference intensities) without knowledge of the alternatives' performance on any of the other attributes (DCLG, 2009). Only after confirming mutual independence with the participants were the partial linear value functions established, as stated in Section 3.10.2.4.

The partial value functions used in MCDA, in certain applications, may be assumed to be linear. In certain applications, however, the value function may be non-linear. An example would be a curved value function showing a gradual change in returns for changes in performance. Additionally, certain value functions may represent specific thresholds in performance after which further incremental changes in the performance may show diminishing or increasing returns in the attribute value score (DCLG, 2009).

Partial value functions, $u_j(g_{ij})$, were tentatively proposed and then confirmed for the seven attributes by the DC participants, who did not suggest any changes. The partial functions

Table 6-2 - Performance matrix of EP alternatives - Decision conference: Case Study

Performance Matrix	Attributes						
	1	2	3	4	5	6	7
Alternatives	PE Security [0=More Security 1=Less Secure]	Adequacy of electricity generation [0=less adequacy 1=More adequacy]	Maintainability of electricity generation [0=Highly Maintainable 3=Not Maintainable]	Cost: Investment, Operation & Maintenance [Billion US$]	Access to modern energy services [0=less access 12=more access]	Impact on global climate [Mton CO_{2eq} emissions]	Impact on local Environment [0=No or Negilible negative impact 3=Major negative impact]
REF	**0.6173**	**0.1685**	**1.022**	**86.0**	**12.00**	**296**	**2.05**
PRVREN	0.6112	0.1674	1.191	101.71	12.0	286.0	1.816
YNGREN	0.5978	0.1592	1.406	144.65	12.0	279.0	1.000
MNIGRD	0.6211	0.1815	1.043	80.34	12.0	297.7	2.074
STDALN	0.6226	0.1815	0.996	76.18	12.0	287.1	2.074
REFDSM	0.6151	0.1926	1.071	68.58	12.0	283.0	2.018
DIVRSI	0.6022	0.2163	1.198	90.19	12.0	278.6	1.867
DIVRSII	0.6022	0.2163	1.198	90.19	12.0	277.2	1.867
DIVRSIII	0.5986	0.1977	1.140	86.14	10.4	268.6	1.867
IDEAL	0	0.25	0	30.0	12.00	200	0
NON-IDEAL	1	0	3	200.0	8.00	300	3

were constructed within the JSMAA value function user interface (Section 3.9.2.5). The partial value function corresponding to Attribute 1, PE Security, is shown in Figure 6-1. This example has a descending value function in which the most preferred performance, g_{ij}, with a score of $u_j(g_{ij}) = 1$, is seen to have a lower value on the x-axis (performance) than the least preferred performance. The partial value functions of the remaining attributes are presented in Subsection D.1 of Appendix D.

After presenting the tentatively proposed partial value functions the participants agreed that they approved of the functions and that they were satisfactory enough to proceed.

With the partial value functions defined, the attribute value matrix could be established.

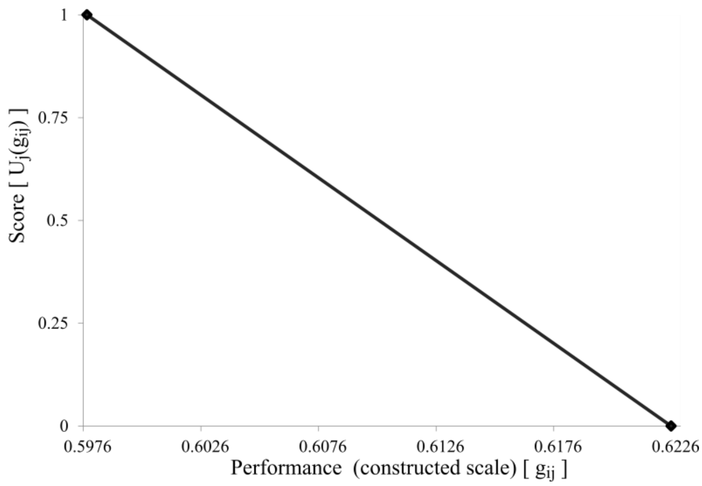

Figure 6-1 - Partial value function - Attribute 1 PE security: Case study

The attribute value matrix was established and presented to the participants. The attribute value matrix presented below in Table 6-3, maps the performance of the alternatives into values that can be aggregated together using the chosen additive form of the preference function as defined in Eq. 3-22 in Section 3.9.2.1.

Table 6-3 - Attribute value matrix of EP alternatives - Decision conference: Case Study

Scoring Matrix / Alternatives	Attributes 1 PE Security	2 Adequacy of electricity generation	3 Maintainability of electricity generation	4 Cost: Investment, Operation & Maintenance	5 Access to modern energy services	6 Impact on global climate	7 Impact on local Environment
REF	-	-	-	-	-	-	-
PRVREN	0.46	0.14	0.52	0.56	1.00	0.40	0.24
YNGREN	1.00	0.00	0.00	0.00	1.00	0.64	1.00
MNIGRD	0.06	0.39	0.89	0.85	1.00	0.00	0.00
STDALN	0.00	0.39	1.00	0.90	1.00	0.37	0.00
DSMREF	0.30	0.58	0.82	1.00	1.00	0.51	0.05
DIVRSI	0.82	1.00	0.51	0.72	1.00	0.66	0.19
DIVRSII	0.82	1.00	0.51	0.72	1.00	0.70	0.19
DIVRSIII	0.97	0.67	0.65	0.77	0.00	1.00	0.19

6.3.2 Generating preference information

A method of swing weight "ranking" was conducted with participants to establish an order ranking of the ECOWAS+ EP objectives. This swing ranking methodology was described in detail in Section 3.10.2.4.

The method consisted of setting a benchmark case were the performances on all the EP objectives were set at their worst level [0], and a set of others, where each has only one attribute “swung” to its best level [1]. These cases were constructed together with participants in order of preference allowing for a ranking of the cases.

Participants were presented with a visual aid of the EP objectives and corresponding quantifiable attributes to support this process, Figure 6-2. As described next, the participants eventually agreed upon an order of preference of the individual cases that were set in the visual aid. This was used to establish the ranking of the seven importance parameters as shown in Eq. 6-1.

$$k_a \geq k_e \geq k_b \geq k_d \geq k_c \geq k_g \geq k_f \qquad \textbf{Eq. 6-1}$$

Where:

k_j: Importance parameters corresponding to attribute *j* where all *k* are non-negative and $\sum_{j=1}^{n} k_j = 1$

The swing ranking of the objectives required the participants to evaluate their own preferences, or more precisely those representing their institution, as well as to negotiate with fellow participants in the ranking of the EP objectives.

Of particular interest from this activity was the ease at which participants entered into agreement that the objectives to *Maximize PE security* and to *Maximize access to FE supply* should be ranked 1st and 2nd. Choice of the 3rd and 4th ranked objectives, corresponding to the EP objective to *Maximize reliability of the FE supply* and to *Minimize costs*, was more complicated for the group of participants. After prolonged discussion, an impasse was reached. This required a vote to be taken by the participants after lengthy debate due to time constraints on the DC and to ensure that the swing ranking could be completed. The vote resulted in the objective *Maximize reliability of the FE supply* taking the 3rd rank. Following this vote, the objective to *Maximize the maintainability of the FE system* was swung to its best performance, ranking the objective 5th. The Objectives to *Minimize impact on local environment* and *Minimize influence on global climate* were quickly agreed upon by the group to be ranked as 6th and 7th.

In order to compare the results from the evaluation of the EP alternatives, within the three different ECOWAS+, ECOWAS and Developed country EP objective sets, structured previously in Section 3.5, the ranking of objectives was required for all three objective sets.

For the ECOWAS and Developed country objective sets, the ranking of preference information was assumed to be identical to the ECOWAS+ objective ranking, however the objectives that are not present in these sets are removed from the ranking leaving the remaining order of the objectives untouched. Following this method, the ranking of the importance parameters for the ECOWAS and Developed Country Objective sets are shown in Eq. 6-2 and Eq. 6-3, respectively.

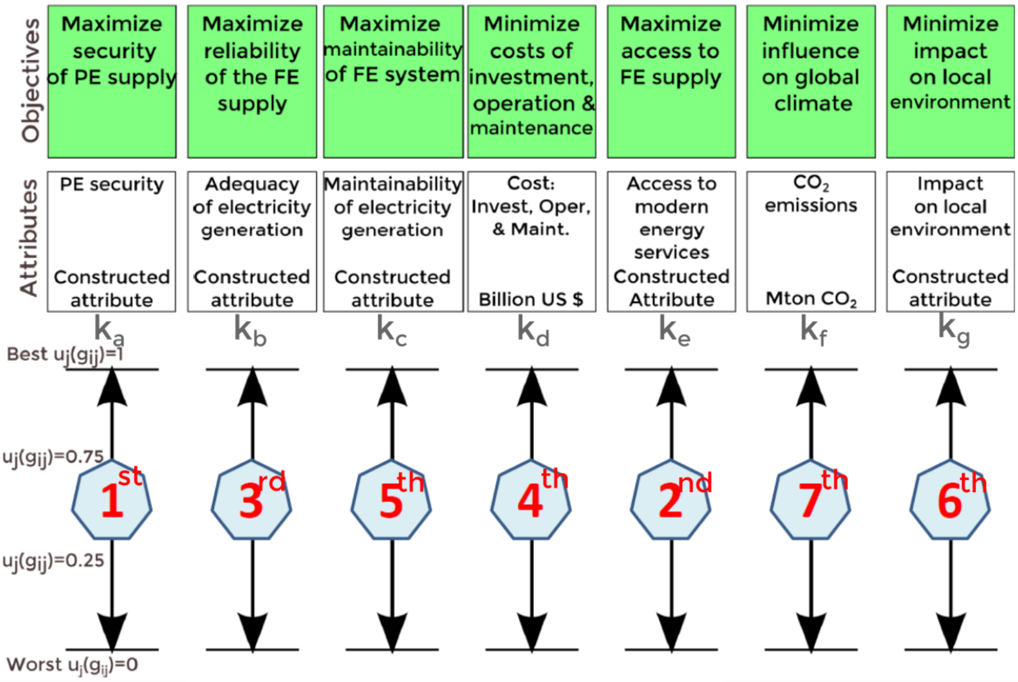

Figure 6-2 - Swing ranking (in red) of the EP objectives - DC: Case Study

The ECOWAS objective set consisted of: Maximize the PE security (k_a); Maximize the reliability of the FE system (k_b); Minimize the cost (k_d), Maximize access to FE (k_e), Minimize the impact on global climate (k_g), and (Minimize the impact on the local environment (k_f). The indices corresponding to the EP objectives are shown in Figure 6-2 and remain the same for all the EP objective sets (e.g. ECOWAS+, ECOWAS, and Developed country), as in Eq. 6-2.

$$k_a \geq k_e \geq k_b \geq k_d \geq k_g \geq k_f \qquad \textbf{Eq. 6-2}$$

The Developed Country objective set indices, Eq. 6-3, consisted of Maximize the PE security (k_a), Maximize the reliability of the FE system (k_b), Minimize the cost (k_d), Minimize the impact on global climate (k_g), and Minimize the impact on the local environment (k_f).

$$k_a \geq k_b \geq k_d \geq k_g \geq k_f \qquad \textbf{Eq. 6-3}$$

This preference information was used in evaluation of the alternatives within each established set of EP objectives (i.e. ECOWAS+, ECOWAS and the Developed Country).

6.3.3 Evaluation of alternatives without preference information: SMAA-2

The SMAA-2 method was used to evaluate the acceptability of the alternatives for the top ranks and to identify which alternatives could be preferred given various possible importance parameter vectors (Tervonen and Lahdelma, 2007; Tervonen, 2014). Importance parameter vectors, discussed in Section 3.9.2.1, are a numerical representation of the preference information corresponding to the chosen set of attributes used in the evaluation of alternatives. Evaluating with no preference information provides results on the number of possible importance parameter vectors that would result in an alternative achieving each of the rankings.

Evaluation with no preference information was conducted only within the ECOWAS+ objective set to provide DMs with information on how different importance parameter value combinations affect the most preferred alternative.

The rank acceptability indices of the alternatives shown in Figure 6-3 presents the alternatives ordered by holistic acceptability rankings along the horizontal-axis, described in Sub-chapter 3.9.2.5.

Five of the alternatives are seen to have nonzero acceptability for rank 1; however, DIVRSII had the largest rank acceptability with over 50% for the first rank, and approximately 25% acceptability for rank 2. Although DIVRSI did not have acceptability supporting rank 1, it did show acceptability of approximately 50% and 25% for ranks 2 and 3 respectively.

The PRVREN and MNIGRD alternatives had no acceptability supporting the higher ranks and larger acceptability indices for the lower ranks 7 and 8.

Although given no preference information the SMAA-2 evaluation found DIVRSII to be an attractive alternative, it is clear in Figure 6-3 that given certain importance parameter value combinations other alternatives could be the first ranked alternative. To explore these possible importance parameter value combinations the central weight factors had to be evaluated. The central weight factors, discussed in Sub-chapter 3.9.2.5, present the importance parameters, in vector form, that a DM might assign in support of this alternative making it the preferred one. A central weight factor can be considered as representing the distribution of weights that is more favorable to the alternative: weight vectors similar to the central weights are likely to yield the best rank for that alternative.

The central weight factors supporting alternatives in receiving the first rank are shown in Figure 6-4 (note: the vector is not defined for alternatives that do not have rank 1). The confidence factors were reported to be 100% for all the central weight factor vectors unless otherwise stated.[21] The central weight factors for DIVRSII are seen to have more equally distributed importance parameters than the remaining alternatives. STDALN, for example, could be the preferred alternative if attribute 3 received a significantly larger importance parameter than the remaining attributes. The same would be true for DSMREF if attribute 4 had a significantly larger importance parameter than the other six attributes.

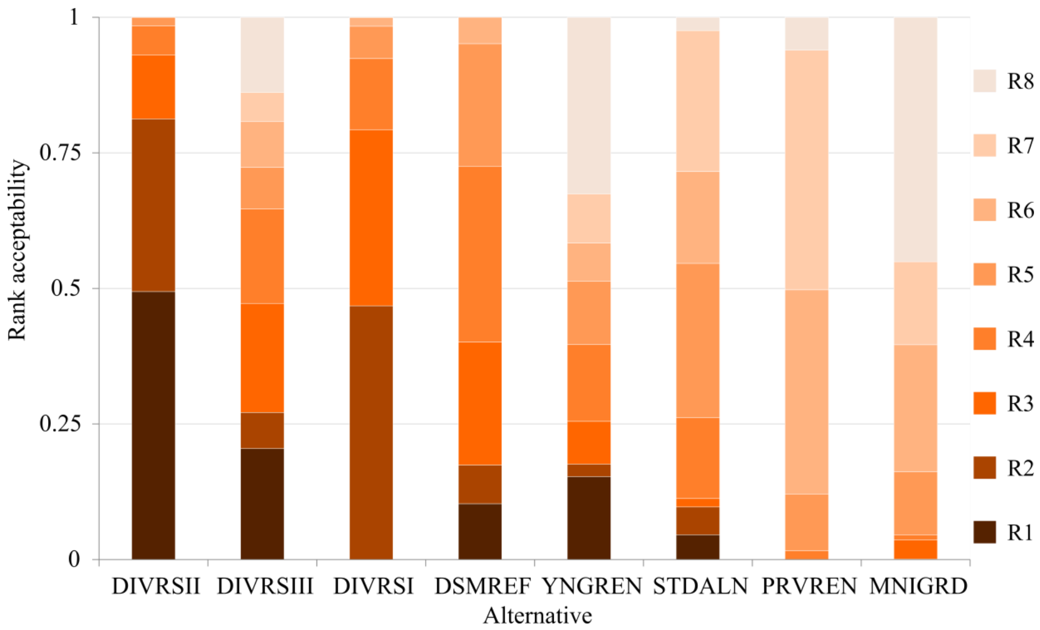

Figure 6-3 - Rank acceptability - No preference information - DC: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index)

6.3.4 Evaluation of alternatives with preference information: SMAA-2

Following the evaluation of the alternatives in the absence of preference information in the previous Section 6.3.3, preference information, in the form of an ordinal ranking of the seven ECOWAS+ EP objectives (Eq. 6-1) was used in the evaluation of the alternatives.

The rank acceptability indexes obtained from the SMAA analysis in the presence of preference information are presented in Figure 6-5. DIVRSII was clearly the most preferred alternative with support of almost 100% of possible importance parameter vectors. The second and third ranks completed the remaining shares of acceptability. DIVRSI replaced DIVRSIII as that with the second largest share of support for the first rank while DIVRSIII fell to the fifth position in the holistic acceptability ranking. DIVRSI clearly had the largest share of second

[21] The confidence factor indicates the probability that an alternative is the best one when its central weights are chosen, taking into account uncertainty about the alternative's performance values. When the performance values are certain, the confidence factor is obviously equal to 1.

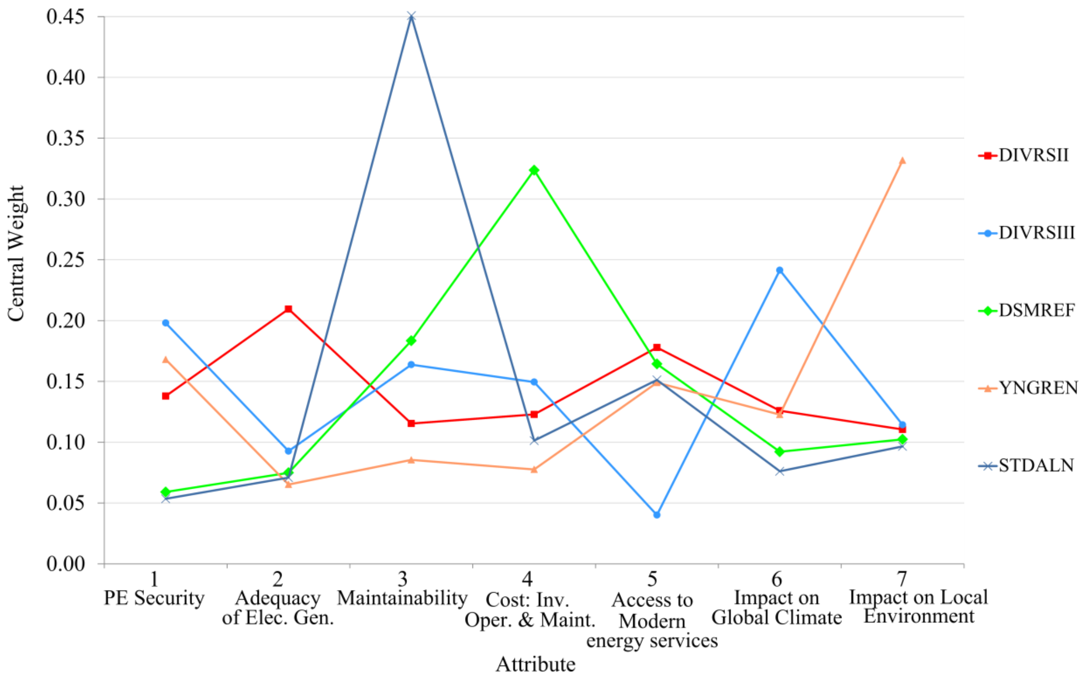

Figure 6-4 - Central weight vectors - No preference information - Def. conf.: Case study

rank importance variable vectors, but none for the first rank. YNGREN was seen to have some first rank acceptability ranking as well as second rank acceptability ranking.

All of the central weight vectors are seen to have similar profiles due to the preference information that was provided, as seen in Figure 6-6. Attributes 1 and 5, PE security and Access to modern energy respectively, had larger central weights factors then the remaining attributes, as required by the constraints (Eq. 6-1). For YNGREN and DIVRSIII to be the favored alternatives, the central weight vectors showed that considerable weight would have to be placed on attribute 1, over 0.6, and less importance on the remaining attributes. DIVERSII was seen to have more weight on attributes 1, 2 and 5 than the remaining attributes. Additionally, the central weights for DIVERSII were more equally divided over all seven attributes than the remaining alternatives with first rank acceptability.

Evaluation of the alternatives within the ECOWAS objective set produced similar results to the ECOWAS+ set with DIVRSII, DIVRSI and YNGREN taking the top holistic acceptability ranks as shown in Figure 6-7. DIVERSII was the most preferred alternative with support of over 80% of possible importance parameter vectors for rank 1 and acceptability for rank 2 completing the remaining shares of acceptability. DIVRSI, while not receiving rank acceptability for the rank 1, received the largest share of second rank importance variable vectors. YNGREN received a larger rank acceptability for rank 1 in the ECOWAS objective set than in the ECOWAS+ set.

The central weight vectors for DIVRSII and YNGREN, the alternatives with rank acceptability for rank 1, in the ECOWAS objective set, are shown in Figure D- 14 of Appendix D.

Within the Developed Country (Dev-C.) set, DIVRSII remained in the top holistic acceptability position with approximately 50% of the possible importance parameter vectors for rank 1, as shown in Figure 6-8. DIVRSIII and DIVRSI received the second and third holistic ranking positions, as DIVRSIII had just under 50% of the possible importance vectors for rank 1 and DIVRSI had just under 50% of the importance vectors for rank 2. Here YNGREN was seen to fall to the 4th holistic ranking position with a small share of rank acceptability for ranks 1 and 2 and over 70% share of acceptability for rank 4.

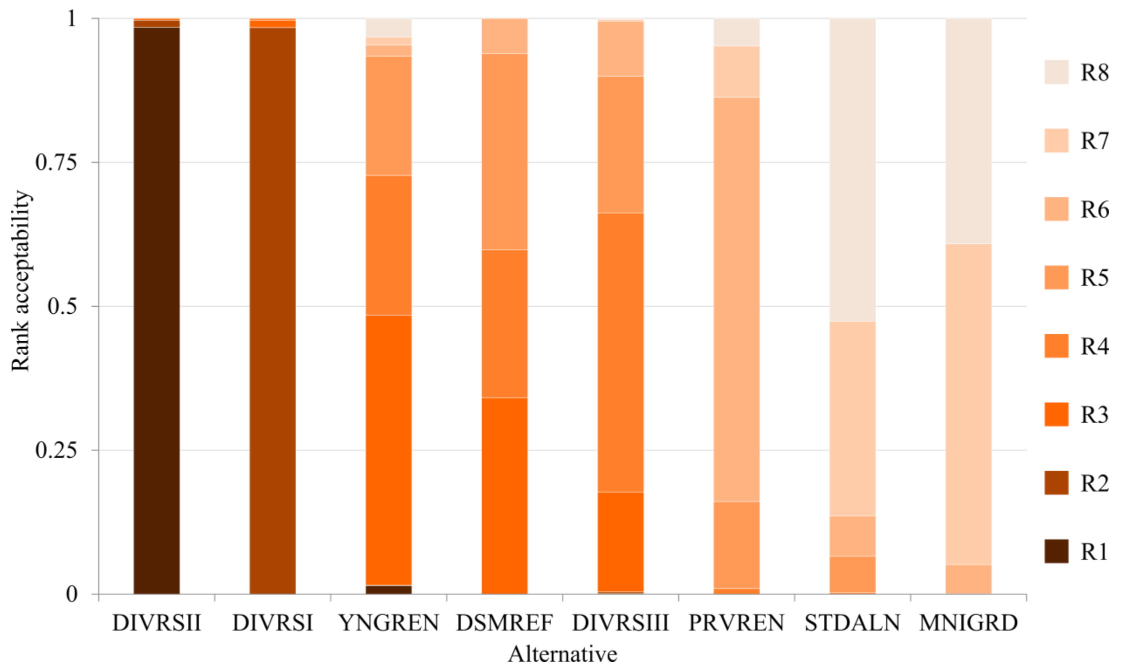

Figure 6-5 - Rank acceptabilities - ECOWAS+ objective set - DC: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index)

The central weight vectors for DIVRSII, DIVRSIII and YNGREN, the alternatives with rank acceptability for rank 1, in the Dev-C, objective set, are shown in Figure D- 15 of Appendix D.

The summary of the evaluation with SMAA-2 is presented in section 6.3.6 the Summary of Evaluation of the EP alternatives.

As presented in the multicriteria evaluation methods chosen for the current work, Section 3.10, following the evaluation of the alternatives within the SMAA-2 methodology, VIP Analysis was employed to evaluate the alternatives. The SMAA-2 methodology was employed to evaluate the alternatives in the absence of preference information and to evaluate the rank acceptabilities of the alternatives as well as the central weight vectors of those with rank 1 acceptabilities. The VIP Analysis provided additional information on the range of values that alternatives could achieve, see Section 3.9.2.1. Additionally, VIP Analysis allowed for the introduction of constraints based on the preferences of the DMs, and comparison of the non-dominated alternatives, as described in the Section 3.9.2.4 on VIP Analysis.

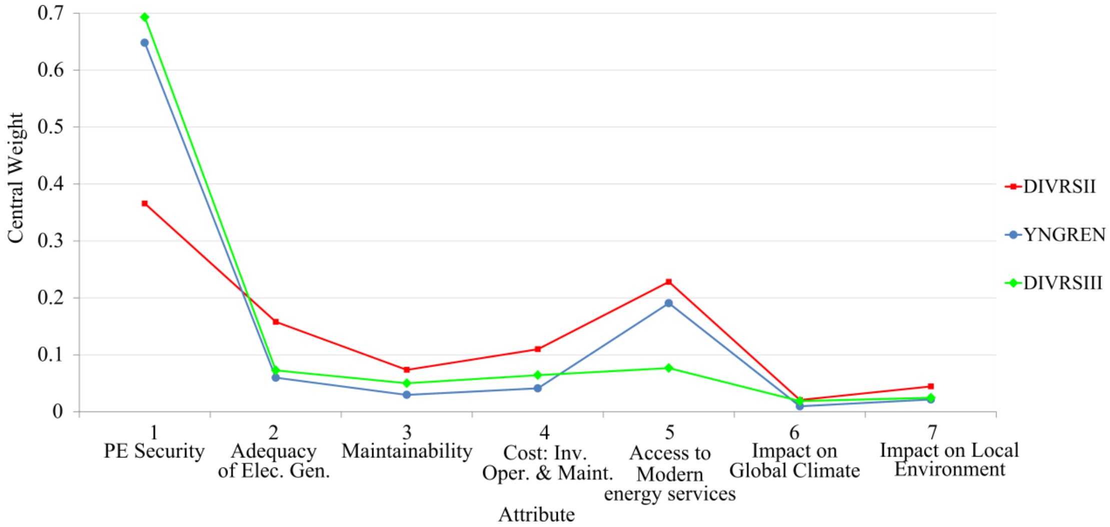

Figure 6-6 - Central weight vectors - ECOWAS+ objective set - DC: Case study

6.3.5 Evaluation of alternatives with preference information: VIP Analysis

Evaluation within VIP Analysis was conducted given the constraints constructed from the preference information elicited from the DC participants (Section 6.3.2). The constraints were in the form of the ordinal ranking of the EP objectives.

The range of possible values, subsequently referred to as *the range of values*, which each alternative may achieve for all acceptable parameter value vectors, given the constraints, is shown in Figure 6-9. DIVRSII and DIVRSI were seen to have the highest minimum values here. Alternatives DIVRSIII and YNGREN had the highest maximum values, however they were also seen to have a large range of plausible values that had less attractive minimum values. MNIGRD and STDALN appeared to be the most unattractive alternatives, given their low minimum values and maximum values that were not competitive with the remaining alternatives.

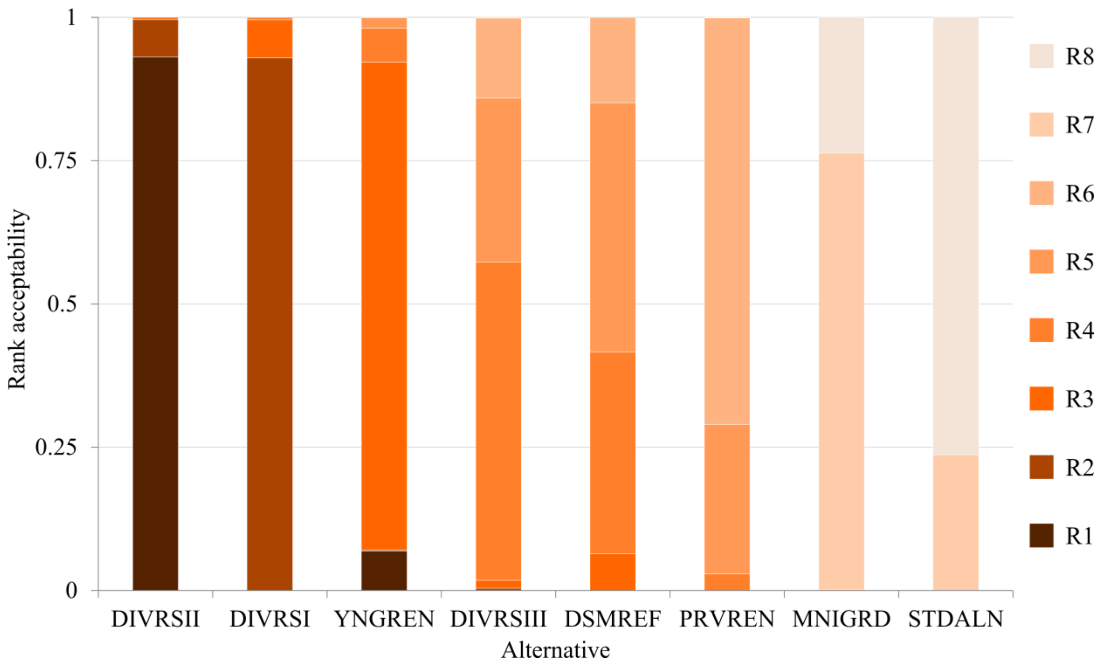

Figure 6-7 - Rank acceptabilities - ECOWAS objective set - DC: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index)

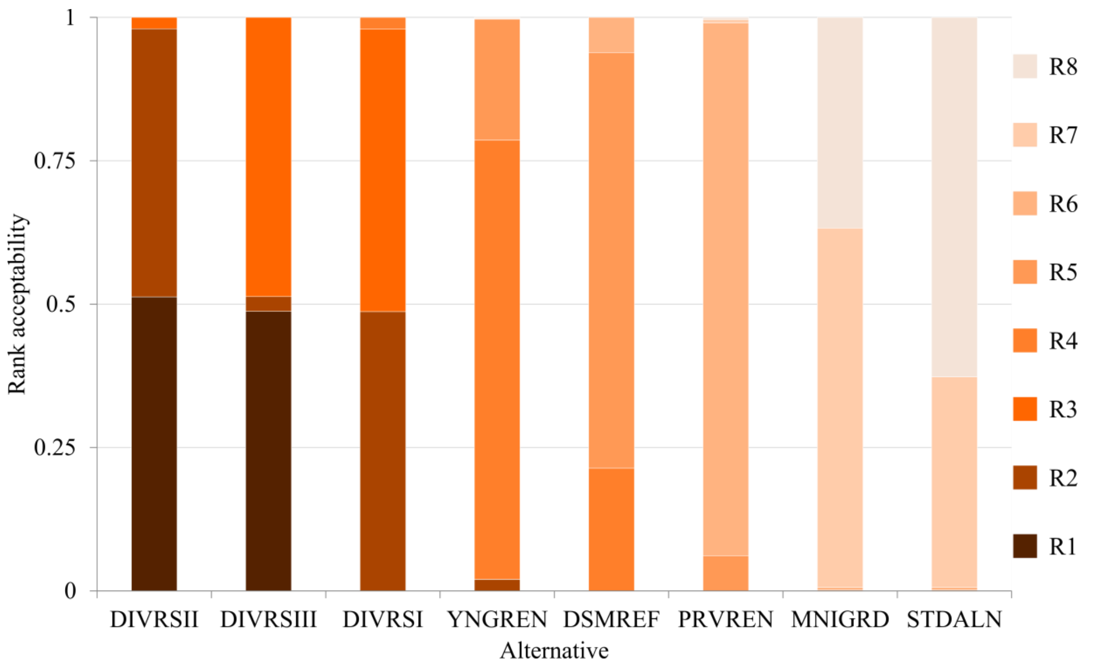

Figure 6-8 - Rank acceptabilities - Dev-C objective set - DC: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index)

VIP Analysis allows for the filtering out of dominated alternatives from the results. Both PRVREN and DSMREF were dominated by DIVRSI and DIVRSII. Both MNIGRD and STDALN were dominated by DSMREF, DIVRSI, and DIVRSII. Filtering for the non-dominated alternatives, the field of alternatives is seen to be limited to four, as shown in Figure 6-10.

The confrontation table from VIP Analysis is shown in Table 6-4 for the ECOWAS+ objective set evaluation. The confrontation table presents the maximum advantage that the alternative in each row has on the alternative represented in the respective columns.

Focusing on these four non-dominated alternatives, the maximum regret of choosing each alternative is represented in the bottom row of the respective column. Here a comparison between DIVRSII and YNGREN showed that the maximum advantage (value difference) DIVRSII could have over YNGREN was 0.409, while the maximum advantage YNGREN could have over DIVERSII was much less (0.179). The maximum regret for each alternative represents the largest difference by which it could be worse than another alternative (value difference). An attractive alternative would therefore have the smallest maximum regret.

In Table 6-4 DIVRSIII is seen to have the largest maximum regret, followed by YNGREN. These two alternatives, which had the highest maximum value in the ranges, shown in Figure 6-10 are therefore seen here, in the confrontation table (Table 6-4), to be less attractive or not attractive at all due to this large maximum regret. DIVRSI and DIVRII were found to have the lowest maximum regrets.

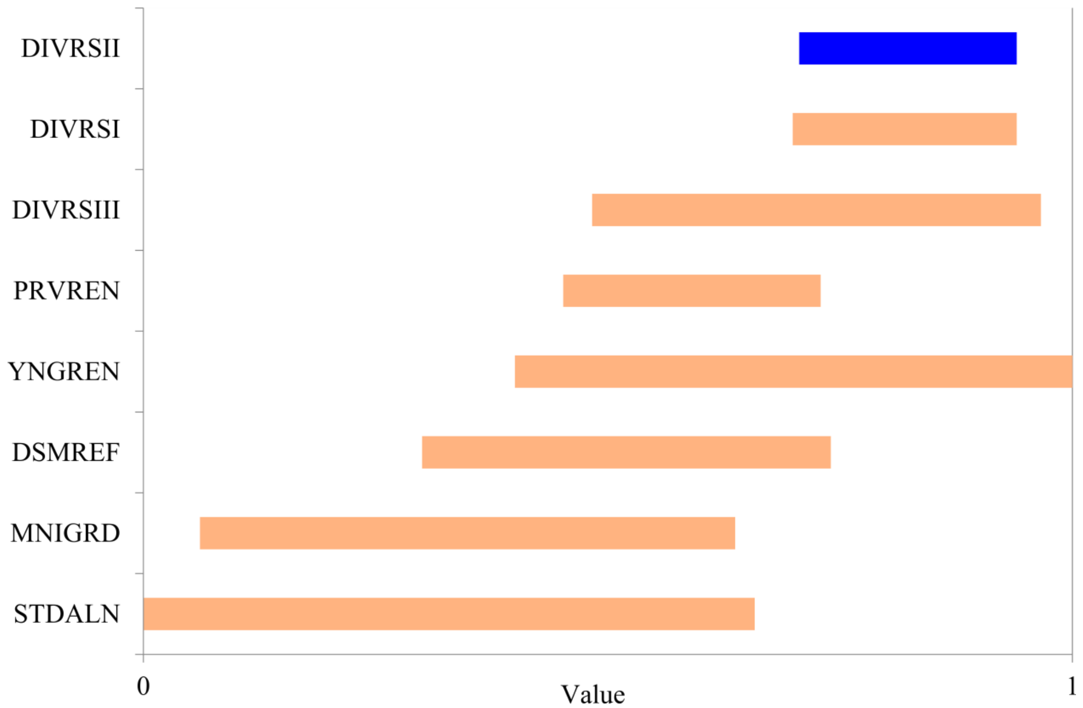

Figure 6-9 - Range of values - ECOWAS+ objective set - DC: Case study

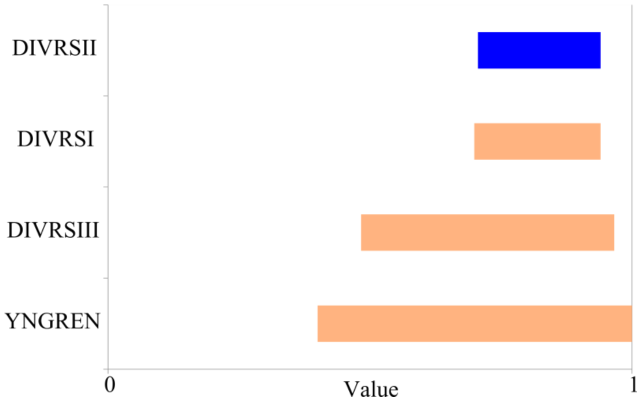

Figure 6-10 - Range of values: non-dominated - ECOWAS+ objective set - DC: Case study

Within the ECOWAS objective set there were no dominated alternatives. The alternatives together with their range of values resulting from the analysis under the ECOWAS objective set are shown in Figure 6-11. Here DIVRSI and DIVRII were seen as attractive results given the high minimum value and high maximum values achievable. DIVRSIII, YNGREN and STDALN present alternatives with the highest maximum values, however they also had low minimum values. The YNGREN and STDALN alternatives were seen to have large ranges of possible values, stretching from 0 to 1.

Table 6-4 - Confrontation table: non-dominated - ECOWAS+ objective set - DC: Case study

	DIVRSII	DIVRSI	DIVRSIII	YNGREN
DIVRSII		0.007	0.427	0.409
DIVRSI	0.001		0.428	0.409
DIVRSIII	0.145	0.144		0.212
YNGREN	0.180	0.179	0.517	
Max Regret	0.180	0.179	0.517	0.409

The confrontation table from VIP Analysis is shown in

Table 6-5 for the ECOWAS objective set evaluation. Examining the confrontation table DIVRSI and DIVRSII were seen to have the lowest max regrets which made them attractive in addition to the high minimum value already observed. YNGREN, STDALN, and MNIGRD had the largest max regrets at, or close to, the maximum value 1.

Comparing with the results from the ECOWAS set of objectives (

Table 6-5) and the ECOWAS+ set of objectives (Table 6-4), DIVRSI, DIVRSII and DIVRSIII remained the attractive alternatives in the evaluation with the ECOWAS set of objectives, however they had comparably larger max regrets. A change was also seen in the range of values and the decreased attractiveness of the YNGREN alternative in the ECOWAS evaluation.

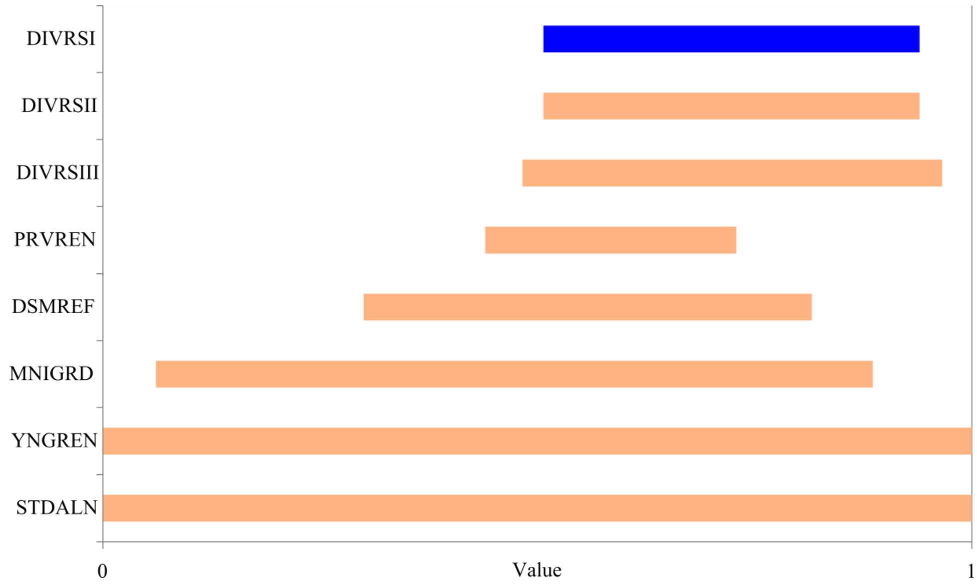

Figure 6-11 - Range of values: non-dominated - ECOWAS objective set - DC: Case study

Table 6-5 - Confrontation table: non-dominated - ECOWAS objective set - DC: Case study

	DIVRSI	DIVRSII	DIVRSIII	PRVREN	DSMREF	MNIGRD	YNGREN	STDALN
DIVRSI		0.001	0.428	0.406	0.521	0.760	0.507	0.821
DIVRSII	0.008		0.427	0.406	0.520	0.759	0.507	0.820
DIVRSIII	0.144	0.145		0.507	0.665	0.904	0.649	0.966
PRVREN	0.016	0.016	0.246		0.158	0.397	0.524	0.458
DSMREF	0.308	0.308	0.167	0.292		0.239	0.816	0.300
MNIGRD	0.378	0.378	0.237	0.362	0.070		0.886	0.061
YNGREN	0.179	0.180	0.517	0.542	0.700	0.939		1.000
STDALN	0.493	0.493	0.351	0.476	0.184	0.114	1.000	
Max Regret	0.493	0.493	0.517	0.542	0.700	0.939	1.000	1.000

Within the Dev-C objective set there were no dominated alternatives. The range of values of the alternatives from the evaluation within the Dev-C set of EP objectives is shown in Figure 6-12. Here DIVRSI and DIVRII were found to have maximum values similar to the remaining alternatives of or close to 1, however they represented the alternatives with the highest minimum values.

YNGREN, STDALN and DIVRSIII had values that range from 0 up to, or approximately, 1. The remaining alternatives were also shown to have low minimum possible values.

The confrontation table from VIP Analysis is shown in Table 6-6 for the Dev-C objective set evaluation. The confrontation table showed that DIVRSI and DIVRSII were the alternatives with the lowest maximum regret. Excluding DSMREF the remaining alternatives had maximum regrets at or close to the extreme value of 1, making them unattractive despite their high maximum values.

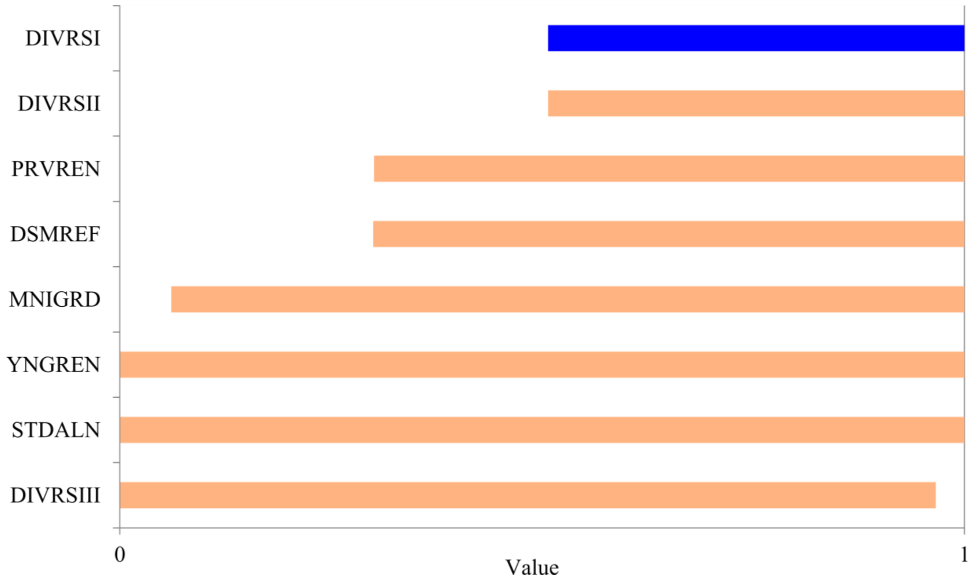

Figure 6-12 - Range of values: non-dominated - Dev-C objective set - DC: Case study

Table 6-6 - Confrontation table: non-dominated - Dev-C objective set - DC: Case study

	DIVRSI	DIVRSII	PRVREN	DSMREF	MNIGRD	YNGREN	STDALN	DIVRSIII
DIVRSI		0.001	0.610	0.521	0.760	0.512	0.821	1.000
DIVRSII	0.009		0.609	0.520	0.759	0.512	0.820	1.000
PRVREN	0.016	0.016		0.158	0.397	0.524	0.458	1.000
DSMREF	0.308	0.308	0.292		0.239	0.816	0.300	1.000
MNIGRD	0.378	0.378	0.362	0.070		0.886	0.061	1.000
YNGREN	0.179	0.180	0.542	0.700	0.939		1.000	1.000
STDALN	0.493	0.493	0.476	0.184	0.114	1.000		1.000
DIVRSIII	0.144	0.145	0.519	0.665	0.904	0.649	0.966	
Max Regret	0.493	0.493	0.939	0.7	0.939	1	0.939	1

Comparing the results from the VIP Analysis evaluation of the ECOWAS+ objective set (Table 6-4) with those from the Dec-C objective set (Table 6-6) the same alternatives DIVRSI and DIVRII were seen as the most attractive. However, they had comparably larger max regrets. DIVRSIII was found to be much less attractive than in the ECOWAS+ set due to the low minimum value and larger max regret in the Dev-C analysis.

6.3.6 Summary of Evaluation of the EP alternatives

A summary of the results from the evaluation of alternatives as part of the case study is shown in Table 6-7. The results here are broken down into those from VIP Analysis and SMAA-2 and further disaggregated into the specific objective sets used in the analysis. All the results reflect the analysis with preference information.

Looking across the objective sets and the resulting ranking of alternatives within the VIP Analysis results, some similarities could be seen. DIVRSI and DIVRSII remained the most attractive alternatives under all three objective set evaluations (The ranking is in order of the least max regret and followed by the largest min values to break any positions that are tied.). Some differences were seen in the rankings beyond the 3rd rank. YNGREN, which was attractive in the ECOWS+ evaluation, was found to be unattractive in both the ECOWAS and Dev-C evaluations. DIVRSIII while not ranked 1st remained an alternative of interest in the ECOWAS+ and ECOWAS sets however became unattractive within the Dev-C evaluation.

Within the SMAA-2 evaluations, DIVRSII remained the top ranked alternative across all three objective set evaluations, as shown in Table 6-7 (The rankings for SMAA-2 are in order of the holistic acceptability rank, described in Section 3.9.2.5 calculated with centroid metaweights as stated in Section 3.10.2.5). DIVRSI, which was not found to have rank acceptability for rank 1, was seen to have remained ranked either 2nd or 3rd for all the objective set evaluations, given that it had rank acceptability for the 2nd and 3rd ranks in all the objective sets. YNGREN and DIVRSIII were also seen to be attractive alternatives in the top 5 ranked positions across all three of the objective set evaluations. DIVRSIII was of interest here as it did show a significant change from the fifth rank to the 2nd rank in the ECOWAS+ and Dev-C objective set evaluations respectively.

In summary, there was little change in the resulting top ranked alternatives between each of the three sets of objectives used in the evaluation. This was true both within the VIP Analysis and the SMAA-2 methodologies. The top ranked alternatives DIVRI and DIVRII in one order or another remained common across all the objective sets as well as between the two evaluation methodologies.

Table 6-7 – Summary of results- DC: Case Study

	VIP Analysis[1]			SMAA-2[2]		
Ranking	ECOWAS+	ECOWAS	Dev-C	ECOWAS+	ECOWAS	Dev-C
1	**DIVRSI**	**DIVRSI**	**DIVRSI**	**DIVRSII**	**DIVRSII**	**DIVRSII**
2	**DIVRSII**	**DIVRSII**	**DIVRSII**	DIVRSI	DIVRSI	**DIVRSIII**
3	**YNGREN**	**DIVRSIII**	**PRVREN**	**YNGREN**	**YNGREN**	DIVRSI
4	**DIVRSIII**	**PRVREN**	**DSMREF**	DSMREF	DIVRSIII	**YNGREN**
5	PRVREN	**DSMREF**	**MNIGRD**	**DIVRSIII**	DSMREF	DSMREF
6	DSMREF	**MNIGRD**	**YNGREN**	PRVREN	PRVREN	PRVREN
7	MNIGRD	**YNGREN**	**STDALN**	STDALN	MNIGRD	MNIGRD
8	STDALN	**STDALN**	**DIVRSIII**	MNIGRD	STDALN	STDALN

1. Sorted in order of value for max regret w/ min value as a "tie breaker". Non-dominated alternatives in Bold.
2. Sorted in order of descending holistic acceptability indices. Alternatives with rank acceptabilty for R1 in Bold.

6.4 Expanded EP 2008-2020 alternative set.

To supplement the original eight alternatives, seven additional alternatives were constructed to further explore the decision space. These seven additional alternatives are presented in Table 6-8 and described in detail in the sections that follow.

Table 6-8 – Additional EP alternatives for sensitivity analysis – Case study

Alternative		Brief narrative of the alternative
9	UNIMOD Universal access & modern services	Presents a set of actions to bring about universal access to the modern energy carriers of electricity and LPG. Policies are implemented to shift of cooking and water heating services provided by fuelwood and charcoal to electric and LPG. Actions also shift kerosene lighting to electric lighting.
10	DIVPES Diverse PE supply	Consists of a set of actions to diversify the number of PE resources as well as the resources in the PE supply for electricity generation. This is accomplished by expanding the indigenous renewables in the PE supply as well as introducing coal fired electricity generation into the mix.
11	LOWINV Lowest investment cost	Consists of a set of actions to limit the overnight investment cost of electricity generation technologies. This is accomplished first through DSM efforts to decrease FE demand and in turn the peak demand required to be met by installed generation capacity. Generation capacity with the lowest investment cost is favored.
12	LOWRUN Lowest running cost	Consists of a set of actions to limit the running cost of electricity generation technologies, i.e. maintenance, operation and fuel. This is accomplished first through DSM efforts to decrease FE demand required to be met by installed generation capacity. Generation capacity with the lowest running cost is favored.
13	LOCREC Local energy resources	Consists of a set of actions that favor technologies that harness local PE resources for electricity generation and for provision of FE services at the household level. The local PE resources considered for the planning horizon consist of large hydro and other renewables, e.g. wind, solar radiation, and marine energy. Electricity access efforts favor standalone, household level solar PV, technologies for new rural connections. DSM efforts to decrease FE demand for electricity are implemented. Policies also increase the penetration of solar thermal water heaters in the Residential and Service sectors.
14	HGMAIN Highly maintainable	Presents a set of actions that favor electricity generation technologies that are considered to be highly maintainable within the context of Ghana and or SSA.
15	EXPREN Expanded renewables	Consists of a set of actions that seek to expand the share of indigenous renewables both considered proven and young in the context of Ghana and or SSA.

6.4.1 Alt. 9 - Universal access and modern services

The Universal Access & Local Heat Alternative presents a mix of policy actions to bring about universal access to the modern energy carriers of electricity and LPG. Policies are implemented to shift 100% of cooking and water heating services provided by fuelwood and charcoal to electric and LPG. Actions also shift 100% of kerosene lighting to electric lighting. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: With the provision of 100% access of electricity and LPG the Residential sector underwent a 100% shift away from fuelwood and charcoal for cooking and water heating to services provided by electricity and LPG. In addition, a 100% shift to electricity for lighting was made from the previous mix that included kerosene lighting technologies.

DSM activities within the Residential sector were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF (Section 5.10.5).

All remaining FE demand followed the Reference Projection.

Electricity Generation: Electricity generation followed the Reference Projection where installed capacity was predominantly thermal generation consisting of gas turbines and combined-cycle gas turbines. Renewable generation, excluding large hydro, comprised onshore wind and other combustion technologies, as shown in Table 6-9.

The generation capacity, assumed for the current alternative, consisted of 71.5% thermal (GT and CCGT), 21% large hydro, 4.5% wind (onshore), and 3% other combustion (landfill gas, municipal solid wastes, & wood wastes). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

6.4.2 Alt. 10 - Diverse PE supply

The Diverse PE Supply Alternative consists of a mix of actions to diversify the number of PE resources as well as the diversity of the PE supply for electricity generation. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

Electricity Generation: Electricity generation fuel types were diversified with the introduction of coal generation to the mix of thermal generation technologies employed.

The generation capacity, assumed for the current alternative, consisted of 29% thermal-gas (GT and CCGT), 13% thermal-coal, 22% large hydro, 20% wind (on and offshore), 9% other renewables (small wind and hydro, PV, concentrated solar, wave, tidal) and 7% other combustion (landfill gas, municipal solid wastes, and wood wastes). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

6.4.3 Alt. 11 - Lowest investment cost

The Lowest Investment Cost Alternative consists of actions to limit the overnight investment cost of electricity generation technologies. This is accomplished first through DSM efforts to decrease FE demand and in turn the peak demand required to be met by installed generation capacity. Thermal generation capacity, gas turbine (GT) generation technology, with the lowest investment cost [US $/kW] incurred is favored. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections, for all population types, were the same as those in the Reference Projection.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

All remaining FE demand followed the Reference Projection.

Electricity Generation: The electricity generation capacity plan consisted of predominantly additional GT thermal generation capacity due to the lowest investment cost constraint on the selection of technologies. The additional constraint of 7% renewables, excluding large hydro, resulted in the selection of large on-shore wind installations.

The generation capacity, assumed for the current alternative, consisted of 77% thermal-gas (GT), 14% large hydro, and 9% wind (onshore). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

6.4.4 Alt. 12 - Lowest running cost

The electricity generation capacity plan of the Lowest Running Cost Alternative consists predominantly of thermal generation technologies due to a selection constraint that favors the lowest running costs (i.e. operation, maintenance and fuel). This is accomplished first through DSM efforts to decrease FE demand required to be met by installed generation capacity. Thermal generation capacity, CCGT generation technology, with the lowest investment cost [US $/kWh] incurred is favored. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

Electricity Generation: The electricity generation capacity plan consisted of predominantly additional CCGT thermal generation capacity due to the lowest running cost constraint on the selection of technologies. The additional constraint of 7% renewables, non-large hydro, resulted in the selection of large on-shore wind installations.

The installed generation capacity, assumed for the current alternative, in 2020 consisted of 78% thermal-gas (9%GT and 69% CCGT), 14% large hydro, and 8% wind (onshore). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection.

6.4.5 Alt. 13 - Local energy resources

The Local Energy Resources Alternative consists of policies that favor technologies that harness local PE resources for electricity generation and for provision of FE services at the household level. The local PE resources considered for the planning horizon consist of large hydro and other renewables, e.g. wind, solar radiation, and marine energy. Electricity access efforts favor standalone, household level solar PV, technologies for new rural connections. DSM efforts to decrease FE demand for electricity are implemented. Policies also increase the penetration of solar thermal water heaters in the Residential and Service sectors. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for rural populations consisted of 20% grid, 10% minigrid, and 70% standalone. New connections for Core-Urban and Peri-Urban populations remained 100% main grid connections.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative, described previously in Alt. 5 DSMREF.

Electricity Generation: The electricity generation capacity plan favored the installation of technologies harnessing local PE resources. These resources consisted of a mix of renewable resources for the planning horizon.

The generation capacity, assumed for the current alternative, consisted of 35% thermal-gas (GT and CCGT), 24% large hydro, 28% wind (on and offshore), 7% other renewables (small wind and hydro, PV, concentrated solar, wave, tidal) and 6% other combustion (landfill gas, municipal solid wastes, and wood wastes). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection

6.4.6 Alt. 14 – Highly maintainable

The highly maintainable alternative presents a pathway that favor electricity generation technologies that are considered to be highly maintainable within the context of Ghana and or SSA. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

All remaining FE demand followed the Reference Projection.

Electricity Generation: As in the Reference Projection electricity generation was provided predominantly through thermal generation consisting of gas turbines and combined-cycle gas turbines. These generation technologies were those considered most proven and maintainable in the context of Ghana and sub-Saharan West Africa.

The generation capacity consisted of 77% thermal (GT and CCGT), 23% large hydro, and a residual share of other combustion (landfill gas, municipal solid wastes, and wood wastes). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection

6.4.7 Alt. 15 – Expanded renewables

The expanded renewables alternative consists of actions that seek to expand the share of indigenous renewables both considered proven and young in the context of Ghana and or SSA. The constructed alternative is presented below through a description of the main assumptions made.

Electricity access: New connections for all population types were the same as those in the Reference Projection.

Energy Demand: DSM activities within the residential and Service sectors were implemented to reduce the peak demand as described in DSM and Refinery Capacity Alternative. See the DSM activities described previously in Alt. 5 DSMREF.

Additionally, a larger share of water heating was provided by solar thermal water heaters.

Electricity Generation: The electricity expansion plan consisted of a diversification of the PE resources for electricity generation. Unlike PRVREN and YNGREN a mix of renewables considered to be proven and young in the context of Ghana and SSA was included in the installed capacity.

The generation capacity, assumed for the current alternative, consisted of 32% thermal-gas (GT and CCGT), 18% large hydro, 27% wind (on & offshore), 12% other renewables (small wind and hydro, PV, concentrated solar, wave, tidal) and 12% other combustion (landfill gas, municipal solid wastes, & wood wastes). The share of installed capacity by generation technology is shown in Table 6-9. See Appendix C for the detailed capacity expansion plan.

Oil Refining: Followed the Reference Projection.

Transportation: Followed the Reference Projection

6.4.8 Summary of expanded EP 2008-2020 alternatives set

The current section described the assumptions made for the expanded set of seven EP alternatives for the 2008-2020 planning horizon. These EP alternatives were to be evaluated in their achievement of the EP objectives, detailed in Sections 3.5 to 3.6, over that of the Reference Projection, detailed in Sections 5.5 to 5.7. For this reason, the differences between the alternatives and the reference projection over the planning horizon were of specific interest here. A summary of how the EP alternatives presented in the current section diverged from the Reference Projection in the year 2020 is presented in Table 6-9.

The preliminary set of eight EP 2008-2020 alternatives was presented in Section 5.10.9 and summarized in Table 5-62.

Table 6-9 - Summary of divergence of Expanded EP alternatives from the Reference Projection - Ghana 2020

FE Access & Demand Projection for 2020	Reference Projection	Alt. 9 UNIMOD[1]	Alt. 10 DIVPES	Alt. 11 LOWINV	Alt. 12 LOWRUN	Alt. 13 LOCREC	Alt. 14 HGMAIN	Alt. 15 EXPREN
Access rates[2] [%]								
Fuelwood	100 100 100							
Charcoal	80 80 76							
Kerosene	100 90 80							
LPG	53 33 5	100 100 100						
Electricity	100 100 100							
Total FE demand [ktoe]								
Direct solar thermal	52.7							
Fuelwood	10,556.5	4,276.6	7,718.9	7,718.9	7,718.9	7,718.9	7,718.9	7,718.9
Charcoal	3,804.8	102.1	3,026.4	3,026.4	3,026.4	3,026.4	3,026.4	3,026.4
Kerosene – General use	161.0	0.0						
LPG	757.1	4,243.4						
Electricity – Grid[3]	3,050.4	2,537.2	2,457.1	2,457.1	2,457.1	2,333.1	2,457.1	2,457.1
[GWh]	35,469.9 GWh	29,502.4 GWh	28,570.8 GWh	28,570.8 GWh	28,570.8 GWh	27,129.2 GWh	28,570.8 GWh	28,570.8 GWh
Electricity– MiniGrid	44.1	42.8	32.4	32.4	32.4	32.3	32.4	32.4
[GWh]	513.1 GWh	498.0 GWh	376.5 GWh	376.5 GWh	376.5 GWh	375.0 GWh	376.5 GWh	376.5 GWh
Electricity– Standalone	44.1	42.8	32.4	32.4	32.4	255.8	32.4	32.4
[GWh]	513.1 GWh	498.0 GWh	376.5 GWh	376.5 GWh	376.5 GWh	2,625.3 GWh	376.5 GWh	376.5 GWh
Diesel	2,049.9							
Gasoline	1,029.2							
Gasoline– Premix	253.9							
Kerosene– Aviation	214.3							
RFO	655.1							

1. The values presented for the EP 2008-2020 alternatives consist only of those that diverge from those of the Reference Projection.
2. Access rates for the FE carriers refer to the Residential demand sector are presented in the order [CoreUrban PeriUrban Rural] within the respective column.
3. Electricity demand does not include Transmission and distribution losses.

Table 6-9 Continued

PE Supply Projection for 2020	Reference Projection	Alt. 9 UNIMOD	Alt. 10 DIVPES	Alt. 11 LOWINV	Alt. 12 LOWRUN	Alt. 13 LOREC	Alt. 14 HGMAIN	Alt. 15 EXPREN
Share in PE Supply [%]								
Imports	28	69	25	36	31	24	32	25
Indigenous	72	31	75	64	69	76	68	75
PE Supply Import [ktoe]								
Crude oil	1,573.8	1,570.5	4,136.9					
Coal	0.0		645.7					
Natural gas	6,107.0	5,220.8	2,616.5	7,213.2	4,837.9	2,855.0	5,168.1	3,060.7
Kerosene	157.9	0.0	0.0					
LPG	660.3	4,146.6	482.5					
Diesel	1,505.0	1,502.4	315.3	1,481.1	1,481.1	1,481.1	1,481.1	1,481.1
Gasoline	807.5		0.0					
RFO	600.9		501.5					
Electricity	0.0		0.0					
PE Supply Indigenous Resources [ktoe]								
Biomass	27,678.1	4,736.1	21,337.5	21,337.5	21,337.5	21,337.5	21,337.5	21,337.5
Hydro	972.3	811.7	1,043.9	519.9	520.0	1,073.4	804.7	859.5
Wind	49.8	38.6	212.9	72.1	67.3	276.0	0.0	290.0
Solar – for PV	661.9	642.4	565.2	485.6	485.6	2,472.8	485.6	637.0
Solar thermal	52.7							
Marine energy	0.0		249.2			170.9		179.5
Other Renewables[4]	107.3	85.4	653.9	0.0	0.0	494.4	4.0	1,086.5
Transformation - Indigenous Production [ktoe]								
Kerosene –TOR[5]	217.4	214.3	375.3					
LPG-TOR	96.8		274.6					
Diesel-TOR	634.9		1,800.7					
Gasoline-TOR	475.5		1,283.1					
RFO-TOR	54.2		153.6					
Transformation - Installed capacity – Grid Electricity generation shares [%]								
Natural gas	71.3	71.5	28.7	76.9	78.4	34.5	77.0	31.9
Coal	0.0		13.0					
Large hydro	21.0	21.1	21.7	14.2	13.6	24.3	23.0	17.6
Wind	4.9	4.5	19.9	8.9	8.0	28.1	0.0	26.7
Marine	0.0		5.2			3.9		
Renewables – other[6]	0.1	0.1	4.1	0.0	0.0	2.8	0.0	11.8
Combustion – other[7]	2.7	2.8	7.4	0.0	0.0	6.4	0.0	12.0

4. Comprises small hydro, small wind, landfill gas, municipal solid waste, and woodwastes.
5. TOR refers to petroleum based products produced domestically from the Tema Oil Refinery.
6. Small hydro, wind and PV
7. Landfill gas, municipal solid waste and woodwastes

6.4.9 Performance assessment and value scoring of expanded EP 2008-2020 alternative set.

The expanded set of EP alternatives, the preliminary set of EP alternatives, and the reference projection were evaluated in achievement of the ECOWAS+ EP objectives prior to the DC, utilizing the quantifiable attributes detailed in Section 3.6. The performance matrix detailing their performance, on these attributes, was constructed and is presented in Table 6-10.

Table 6-10 - Performance matrix of expanded set of EP alternatives - Decision conference: Case Study ("New" alternatives are distinguished by " * ")

Performance Matrix	Attributes						
	1	2	3	4	5	6	7
Alternatives	PE Security [0=More Security 1=Less Secure]	Adequacy of electricity generation [0=less adequacy 1=More adequacy]	Maintainability of electricity generation [0=Highly Maintainable 3=Not Maintainable]	Cost: Investment, Operation & Maintenance [Billion US$]	Access to modern energy services [0=less access 12=more access]	Impact on global climate [Mton CO_{2eq} emissions]	Impact on local Environment [0=No or Negilible negative impact 3=Major negative impact]
REF	**0.6173**	**0.1685**	**1.022**	**86.0**	**12.00**	**296**	**2.05**
PRVREN	0.6112	0.1674	1.191	101.71	12.0	286.0	1.816
YNGREN	0.5978	0.1592	1.406	144.65	12.0	279.0	1.000
MNIGRD	0.6211	0.1815	1.043	80.34	12.0	297.7	2.074
STDALN	0.6226	0.1815	0.996	76.18	12.0	287.1	2.074
REFDSM	0.6151	0.1926	1.071	68.58	12.0	283.0	2.018
DIVRSI	0.6022	0.2163	1.198	90.19	12.0	278.6	1.867
DIVRSII	0.6022	0.2163	1.198	90.19	12.0	277.2	1.867
DIVRSIII	0.5986	0.1977	1.140	86.14	10.4	268.6	1.867
UNIMOD*	0.5956	0.1921	1.047	69.24	12.0	284.0	2.034
DIVPES*	0.6262	0.1701	1.456	126.82	12.0	284.1	1.869
LOWINV*	0.6326	0.1999	1.131	36.18	12.0	308.0	1.884
LOWRUN*	0.6350	0.1918	1.117	47.36	12.0	272.9	1.897
LOCREC*	0.5943	0.1633	1.478	107.94	12.0	271.4	1.680
HGMAIN*	0.6152	0.2068	0.911	63.17	12.0	280.1	2.104
EXPREN*	0.6079	0.1300	1.720	103.98	12.0	289.8	1.566
IDEAL	0	0.25	0	30.0	12.00	200	0
NON-IDEAL	1	0	3	200.0	8.00	300	3

The attribute value matrix presented below in Table 6-11, maps the performance of the alternatives into values that can be aggregated together using the chosen additive form of the preference function, as defined in Eq. 3-22 in Section 3.9.2.1.

The partial value functions used to establish the attribute value matrix in Table 6-11 were tentatively proposed based on the performance matrix values of the expanded set of alternatives. The partial value functions are presented in Appendix D.

Here it is noted that these partial value functions were proposed post-DC, and that the weight rankings which were established as part of the DC based on the partial value functions previously used in the DC (Section 6.3.2) were assumed to remain unchanged. This was an assumption, as based on the new range of performances (Table 6-10) of the alternatives, the participants' preferences could have changed. However, the range of performances seen in the Expanded Alternatives performance matrix (Table 6-10) did not vary greatly from those seen previously in the DC performance matrix (Table 6-2). The only exception was that of attribute 4, Cost (Billion US dollars), which was [68.58, 144.65] in the DC performance matrix and changed to [36.18, 144.65] in the Expanded Alternatives performance matrix.

6.4.10 Evaluation of expanded alternative set without preference information: SMAA-2

The rank acceptability indices of the full set of 15 alternatives from the SMAA-2 analysis are depicted in Figure 6-13. Eight of the alternatives were seen to have acceptability for rank 1; however, DIVRSII had rank acceptability for rank 1 and the largest remaining acceptabilities for the top 4 rankings. DIVRSI did not have acceptability supporting rank 1, however it did show acceptability for the ranks 2, 3 & 4.

Table 6-11 - Attribute value matrix of expanded set of EP alternatives - Decision conference: Case Study ("New" alternatives are distinguished by " * ")

Attribute Value Matrix Alternatives	1 PE Security	2 Adequacy of electricity generation	3 Maintainability of electricity generation	4 Cost: Investment, Operation & Maintenance	5 Access to modern energy services	6 Impact on global climate	7 Impact on local Environment
REF	-	-	-	-	-	-	-
PRVREN	0.5856	0.4337	0.6537	0.3958	1.0000	0.5585	0.2608
YNGREN	0.9163	0.3387	0.3879	0.0000	1.0000	0.7368	1.0000
MNIGRD	0.3431	0.5970	0.8376	0.5929	1.0000	0.2630	0.0275
STDALN	0.3058	0.5970	0.8957	0.6312	1.0000	0.5322	0.0275
DSMREF	0.4891	0.7250	0.8020	0.7013	1.0000	0.6353	0.0775
DIVRSI	0.8071	1.0000	0.6454	0.5021	1.0000	0.7479	0.2147
DIVRSII	0.8066	1.0000	0.6454	0.5021	1.0000	0.7825	0.2147
DIVRSIII	0.8952	0.7845	0.7174	0.5394	0.0000	1.0000	0.2147
UNIMOD*	0.9683	0.7196	0.8324	0.6952	1.0000	0.6107	0.0633
DIVPES*	0.2177	0.4641	0.3264	0.1643	1.0000	0.6074	0.2125
LOWINV*	0.0587	0.8095	0.7284	1.0000	1.0000	0.0000	0.1997
LOWRUN*	0.0000	0.7165	0.7457	0.8970	1.0000	0.8925	0.1876
LOCREC*	1.0000	0.3853	0.2990	0.3385	1.0000	0.9297	0.3838
HGMAIN*	0.4871	0.8895	1.0000	0.7511	1.0000	0.7101	0.0000
EXPREN*	0.6658	0.0000	0.0000	0.3749	1.0000	0.4636	0.4870

The DIVPES and EXPREN appeared to be the least attractive alternatives with the largest shares of importance parameter variable vectors that resulted in the penultimate and last rankings.

With no preference information, the SMAA evaluation showed multiple alternatives, DIVRSII, HGMAIN, UNIMOD and YNGREN, to be attractive alternatives. However, in the presence of specific importance parameter value combinations, one of these or possibly other alternatives could be the first ranked alternative. The central weight factors provide information on what preference information may result in a certain alternative being the preferred alternative.

The central weight factors that supported alternatives to recieve the first rank for the expanded alternative set are shown in Figure 6-14. Here the central weight vector for DIVRSII was seen to have the largest central weight for attribute 2, while the remaining weight was approximately evenly divided among the remaining attributes. HGMAIN had a central weight vector that supported the alternative for rank 1 when the importance parameter for attribute 3 had a higher value than the other six attributes. HGMAIN and LOCREC had central weight vectors that supported rank 1 when attribute 1 for PE security had the largest weighting. A larger weighting value for attribute 4 for cost would support alternatives LOWINV and LOWRUN in receiving rank 1. Of course these two alternatives were constructed to reflect the lowest investment and running costs in the alternatives.

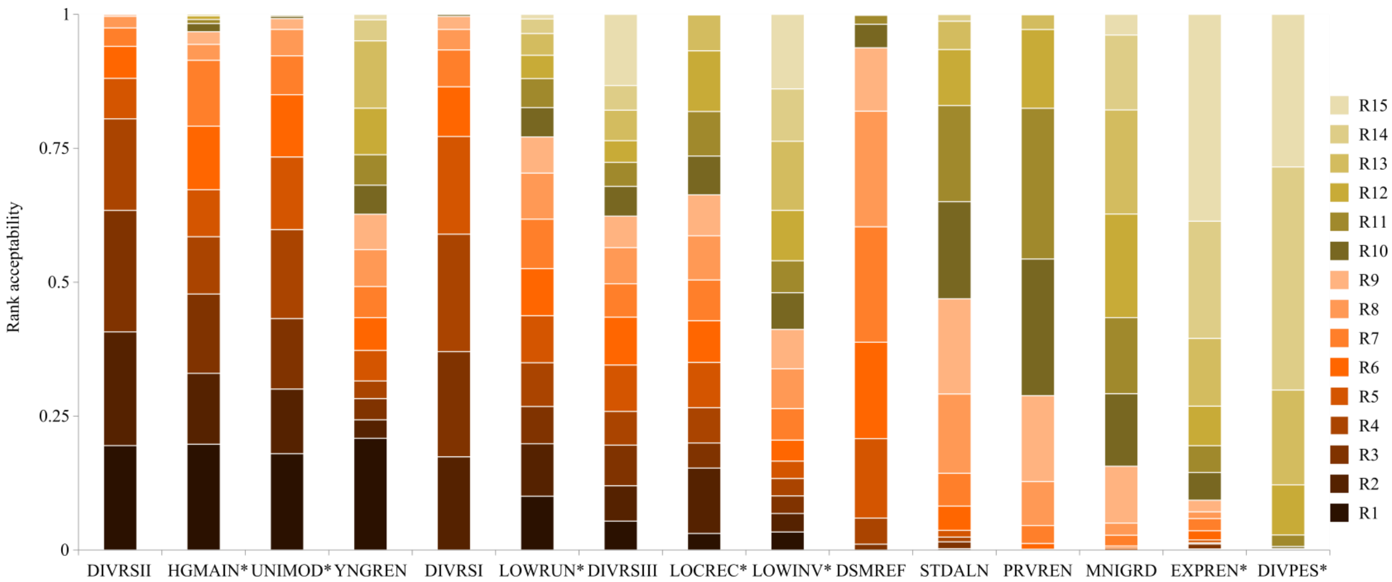

Figure 6-13 - Rank acceptabilities - No preference info. -Expanded alternatives (Exp. alt.): Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and “New” alternatives are distinguished by “ * ”)

6.4.11 Evaluation of expanded EP alternative set with preference information: SMAA-2

Following the evaluation of the expanded set of EP alternatives in the absence of preference information, the set was evaluated with the preference information of the three objective sets, ECOWAS+, ECOWAS and the Dev-C (Section 3.5).

The resulting rank acceptability indices from the SMAA-2 analysis of the expanded set of alternatives are shown in Figure 6-15. Within the ECOWAS+ objective set, UNIMOD was seen to have close to 100% of the possible importance parameter vectors for rank 1, and was clearly the most attractive alternative. DIVRSII was seen to have a small share of rank 1 acceptability and the remaining shares of acceptability were comprised of rank 2 and 3 acceptability.

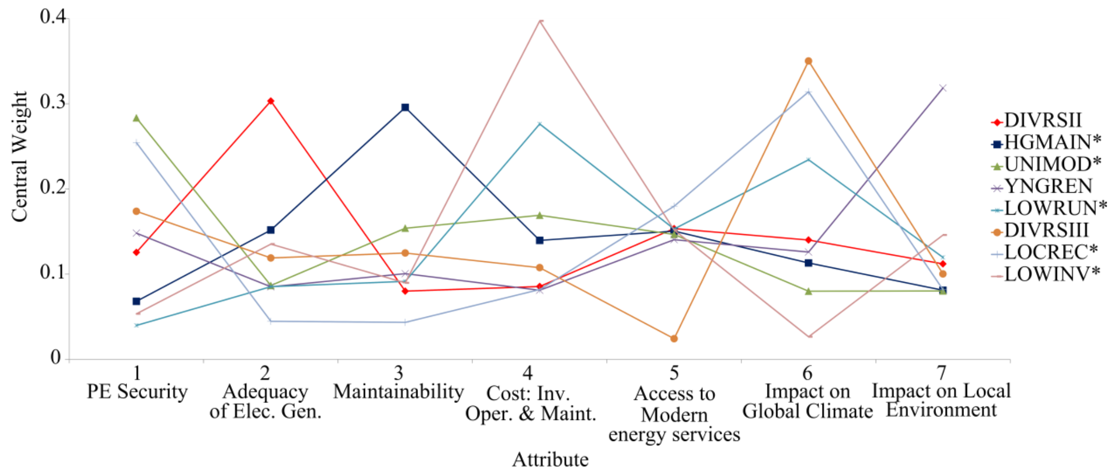

Figure 6-14 – Central weight vectors - No preference info. - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

DIVPES was seen to have over 75% of the possible importance parameter vectors for the last rank 15. This alternative, as well as alternatives positioned to towards the right side of the horizontal axis, had lower holistic acceptability indices and reflected less attractive alternatives within the expanded set.

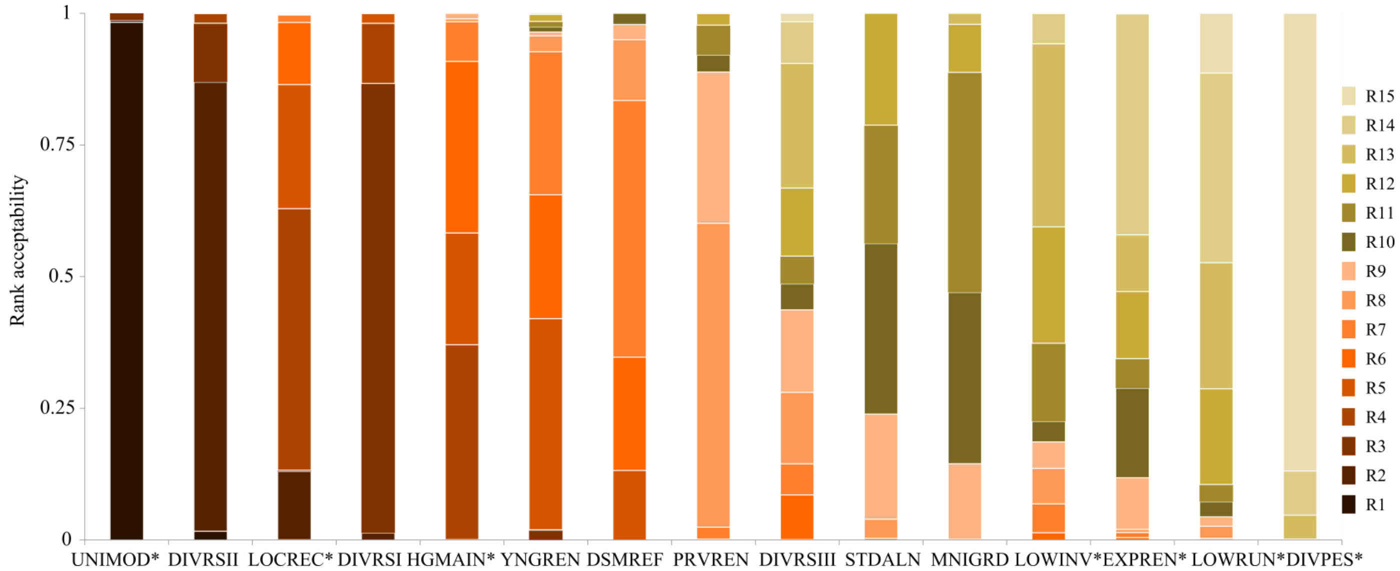

Figure 6-15 - Rank acceptabilities - ECOWAS+ objective set - Exp. alt.: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

The central weight vectors for the alternatives with rank 1 acceptability are shown in Figure 6-16. UNIMOD and DIVRSII had similar central weight vectors, however UNIMOD would place slightly more importance on attribute 1, PE security, and less on attributes 2 and 5, FE system adequacy and cost, than that in DIVRSII. LOCREC had a central weight vector that reflects preference information that places a higher value, approximately 0.8, on attribute 1, PE security than the remaining attributes.

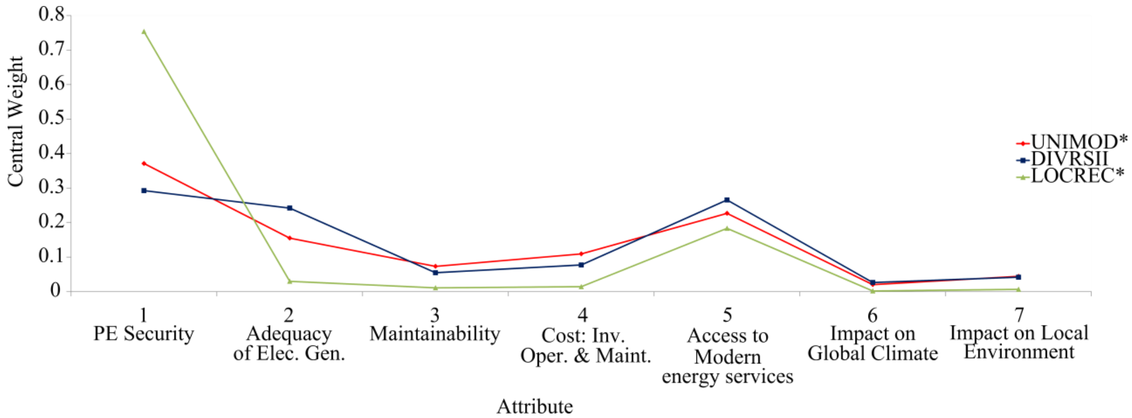

Figure 6-16 - Central weight vectors - ECOWAS+ objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

Shifting to an evaluation of the alternatives within the ECOWAS objective within SMAA-2 methodology some changes were seen in the rank acceptabilities, Figure 6-17, however the holistic ranking, along the horizontal axis was seen to remain similar to the ECOWAS+ holistic ranking. UNIMOD remained the most attractive alternative with over 75% of possible importance parameter vectors for rank 1. The possible importance parameter values for DIVRSII increased slightly to approximately 16%, while the remaining share was comprised of shares for the top 4 ranks. DIVPES, LOWRUN, LOWINV and STDALN continued to have the largest rank acceptability for the last ranks.

In comparison to the ECOWAS+ objective set, the most attractive alternatives remained the same, however YNGREN and HGMAIN traded positions as the 5^{th} and 6^{th} ranked according to the holistic acceptability indices. Additionally, UNIMOD had a lower rank acceptability for rank 1.

The central weight vectors for UNIMOD, and DIVRSII, the alternatives with rank acceptability for rank 1, in the ECOWAS objective set, are shown in Figure D- 16 of Appendix D.

The rank acceptability indices for the expanded set of alternatives evaluated in the SMAA-2 methodology with the Dev-C objective set are shown in Figure 6-18. Within the Dev-C objective set, UNIMOD remained the most attractive alternative in terms of rank acceptability for the top rank as well as the holistic acceptability index as the remaining shares of acceptability were for the top 4 ranks. DIVRSII, DIVRIII and LOCREC also received acceptability indices for Rank 1. DIVRSII had a lower share of rank acceptability for rank 1; however, the remaining shares of rank acceptability were comprised of possible importance parameter vectors for ranks 2, 3 and 4 that made it also an attractive alternative.

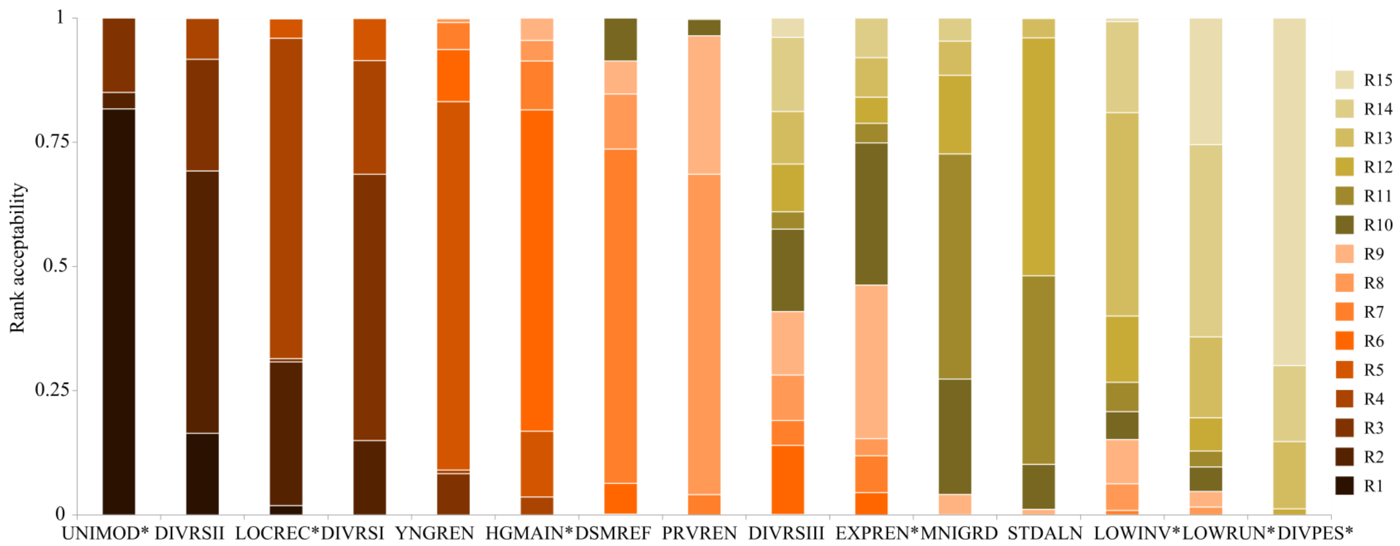

Figure 6-17 - Rank acceptabilities - ECOWAS objective set - Exp. alt.: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

Comparing the results from the Dev-C set with those of the ECOWAS+ set, some changes were seen in the holistic acceptability ranking of the alternatives. UNIMOD remained in the top ranked position, however LOCREC fell to the 4th ranked position and DIVRSIII became more attractive climbing from the 9th ranked position to the 3rd ranked positon. DIVPES, LOWRUN, STDALN and MNIGRD remained the least attractive alternatives in the holistic acceptability index ranking.

The central weight vectors for UNIMOD, DIVRSII, DIVRSIII and LOCREC, the alternatives with rank acceptability for rank 1, in the Dev-C, objective set, are shown in Figure D- 17 of Appendix D.

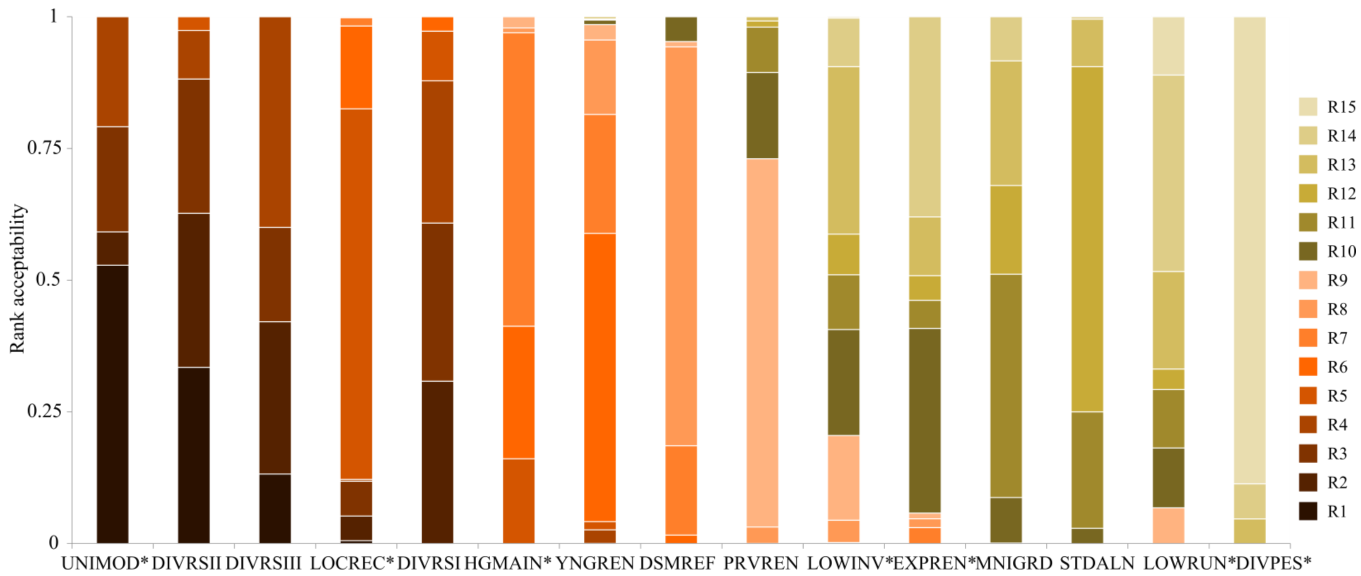

Figure 6-18 - Rank acceptabilities - Dev-C objective set - Exp. alt.: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

6.4.12 Evaluation of expanded EP alternative set with preference information: VIP Analysis

The expanded set of EP alternatives was also evaluated within the VIP Analysis methodology. This consisted of evaluations within the ECOWAS+, ECOWAS and Dev-C objective sets.

The range of values that each alternative could achieve for all acceptable parameter value vectors, given the constraints, resulting from the evaluation of the full set of alternatives under the ECOWAS+ objective set, is shown in Figure 6-19. Here the range of possible values, given constraints corresponding to the ordinal ranking of the EP objectives, is seen. UNIMOD, DIVRSI and DIVRSII were found to have high minimum values as well as attractive maximum values. LOCREC had an attractive maximum possible value of 1, however with a large range of values it was also seen to have a lower minimum value than the alternatives that it follows. LOWINV and LOWRUN were seen to have the lowest minimum values.

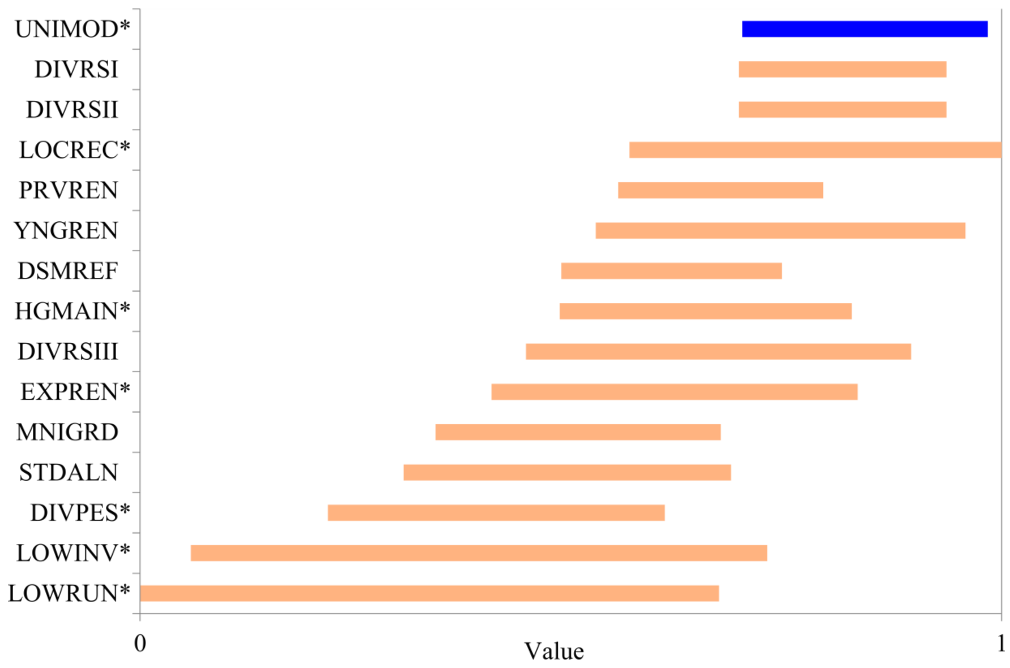

Figure 6-19 - Range of values - ECOWAS+ objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

The range of values figure was filtered for the non-dominated alternatives to limit the alternatives of evaluation. This filtered set of alternatives is shown in Figure 6-20. PRVREN was dominated by DIVRSI, DIVRSII, and UNIMOD. YNGREN was dominated by UNIMOD. Both MNIGRD and STDALN were dominated by DSMREF, DIVRSI, DIVRSII, UNIMOD and LOCREC. DSMREF was dominated by DIVRSI, DIVRSII and UNIMOD. DIVRSIII was dominated by UNIMOD and LOCREC. DIVPES was dominated by PRVREN, YNGREN, MNIGRD, STDALN, DSMREF, DIVRSI, DIVRSII, UNIMOD, LOCREC and HGMAIN. Both LOWINV and LOWRUN were dominated by DIVRSI, DIVRSII, UNIMOD and HGMAIN. HGMAIN was dominated by UNIMOD. EXPREN was dominated by YNGREN, DIVRSI, DIVRSII, UNIMOD and LOCREC. UNIMOD, DIVRSI, DIVRSII, and LOCREC were found to be non-dominated.

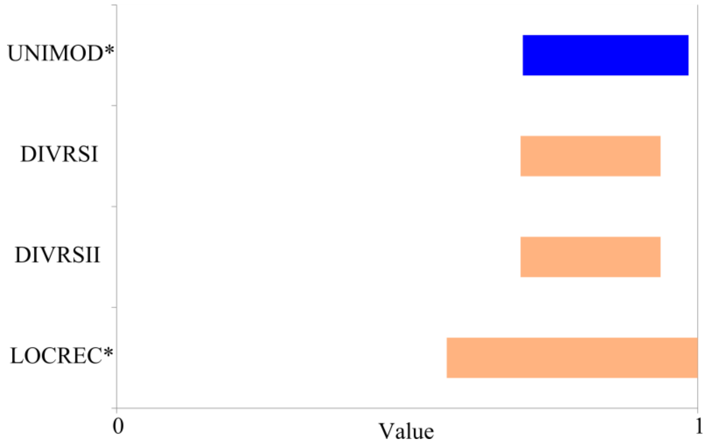

Figure 6-20 - Range of values: non-dominated - ECOWAS+ objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

To provide further insight into the attractiveness of the alternatives, the confrontation table corresponding to the ECOWAS+ set is shown in Figure 6-9. The confrontation table presents the maximum advantage which the alternative in each row has on the alternative represented in the respective columns. The maximum regret from each column is represented in the bottom row. The maximum regret for each alternative represents the largest maximum disadvantage when compared to another alternative. An attractive alternative would therefore have the smallest maximum regret. Here UNIMOD was found to have the least maximum regret of the alternatives. LOCREC was seen to have the largest maximum regret as UNIMOD had a maximum advantage over the alternative of 0.239. DIVRSI and DIVRSII had maximum regrets of 0.193 which corresponded to the maximum advantage of LOCREC over these alternatives. The max regret is discussed in Section 3.9.2.4, and additional information can be found in Dias and Climaco (2000).

Table 6-12 - Confrontation table- ECOWAS+ objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

	UNIMOD*	DIVRSI	DIVRSII	LOCREC*
UNIMOD*		0.161	0.162	0.239
DIVRSI	0.040		0.001	0.186
DIVRSII	0.040	0.005		0.186
LOCREC*	0.032	0.193	0.193	
Max Regret	0.040	0.193	0.193	0.239

The non-dominated alternatives from the ECOWAS set of objectives evaluation is shown in Figure 6-21. PRVREN was dominated by DIVRSI, DIVRSII, UNIMOD and LOCREC. YNGREN was dominated by UNIMOD. Both MNIGRID and STDALN were dominated by DSMREF, DIVRSI, DIVRSII, UNIMOD, LOCREC and HGMAIN. DSMREF was dominated by DIVRSI, DIVRSII and UNIMOD. DIVRSIII was dominated by YNGREN, UNIMOD and LOCREC. DIVPES was dominated by

PRVREN, YNGREN, MNIGRD, STDALN, DSMREF, DIVRSI, DIVRSII, UNIMOD, LOCREC and HGMAIN. The LOWINV alternative was dominated by DIVRSI, DIVRSII, UNIMOD, and HGMAIN. LOWRUN was dominated by DIVRSI, DIVRSII, UNIMOD, LOCREC and HGMAIN. HGMAIN was dominated by DIVRSI, DIVRSII and UNIMOD. EXPREN was dominated by YNGREN, DIVRSI, DIVRSII, UNIMOD and LOCREC. In Figure 6-21 DIVRSI and DIVRSII are seen to have the highest minimum values. UNIMOD and LOCREC were found to have advantageous maximum values, however they also corresponded to the lowest minimum values.

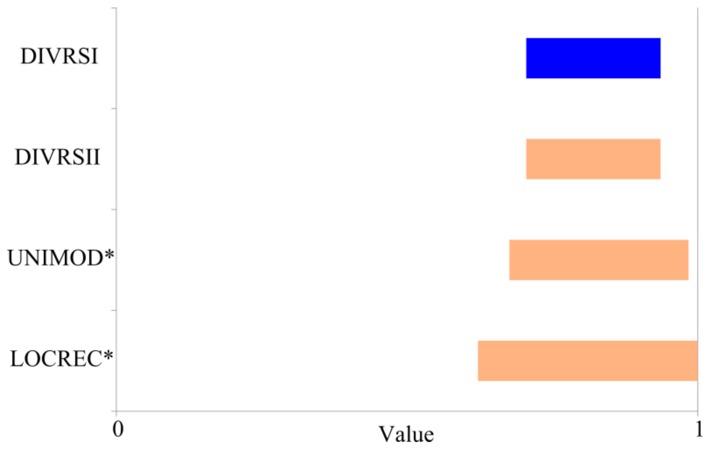

Figure 6-21 - Range of values: non-dominated - ECOWAS objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

The confrontation table of the ECOWAS set of objectives evaluation in VIP Analysis is shown in Table 6-13. In the confrontation table UNIMOD is seen to have the lowest maximum regret, despite the low minimum value that it may have, making it an attractive alternative nonetheless. The LOCREC alternative also had a maximum regret that was smaller than those of alternatives DIVRSI and DIVRSII.

In comparison to the ECOWAS+ objective set, the attractive, non-dominated alternatives remained the same, and UNIMOD had the lowest maximum regret. Here the DIVRSI and DIVRSII had the highest minimum values as opposed to the UNIMOD alternative in the ECOWAS+ set.

Table 6-13 - Confrontation table- ECOWAS objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

	DIVRSI	DIVRSII	UNIMOD*	LOCREC*
DIVRSI		0.001	0.040	0.146
DIVRSII	0.006		0.041	0.146
UNIMOD*	0.161	0.162		0.165
LOCREC*	0.193	0.193	0.032	
Max Regret	0.193	0.193	0.041	0.165

The range of values of the non-dominated alternatives from the evaluation of the full set of alternatives within the Dev-C objective set is shown in Figure 6-22. PRVREN was dominated by DIVRSI, DIVRSII, DIVRSIII, UNIMOD and LOCREC. The YNGREN alternative was dominated by UNIMOD and LOCREC. Both MNIGRD and STDALN were dominated by DSMREF, DIVRSI, DIVRSII, DIVSIII, UNIMOD, LOCREC, and HGMAIN. DSMREF was dominated by DIVRSI, DIVRSII, DIVSIII and UNIMOD. DIVRSIII was dominated by UNIMOD. DIVPES was dominated by PRVREN, YNGREN, MNIGRD, STDALN, DSMREF, DIVRSI, DIVRSII, DIVRSIII, UNIMOD, LOCREC, and HGMAIN. The LOWINV alternative was dominated by DSMREF, DIVRSI, DIVRSII, DIVRSIII, UNIMOD, and HGMAIN. LOWRUN was dominated by DSMREF, DIVRSI, DIVRSII, DIVRSIII, UNIMOD, LOWINV, LOCRED and HGMAIN. HGMAIN was dominated by DIVRSI, DIVRSII, DIVRSIII and UNIMOD. EXPREN was dominated by YNGREN, DIVRSI, DIVRSII, DIVRSIII, UNIMOD, and LOCREC. In Figure 6-22 UNIMOD is seen to have the highest minimum value and an attractive maximum possible value. LOCREC had the largest range with a maximum value of 1.

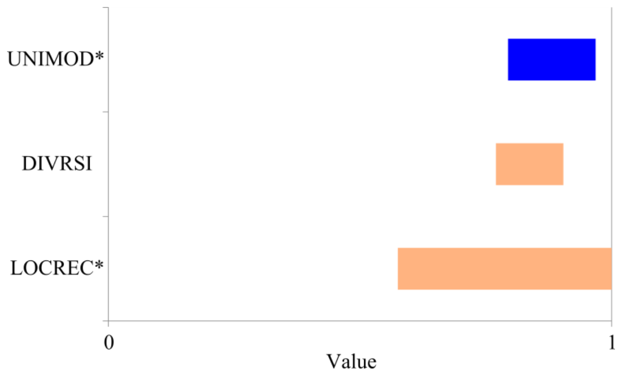

Figure 6-22 - Range of values: non-dominated - Dev-C objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

The confrontation table from the VIP Analysis of the full set of alternatives is shown in Table 6-14. Here the UNIMOD alternative is shown to have the least maximum regret.

In comparison to the ECOWAS+ objective set, the UNIMOD remained the most attractive alternative in terms of minimum value and the maximum regret. DIVRSII was a dominated alternative in the Dev-C objective set, unlike in the ECOWAS+ results.

Table 6-14 – Confrontation table- Dev-C objective set – Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

	UNIMOD*	DIVRSI	LOCREC*
UNIMOD*		0.161	0.220
DIVRSI	0.060		0.211
LOCREC*	0.032	0.193	
Max Regret	0.060	0.193	0.105

6.4.13 Summary of evaluation of the expanded EP alternative set

A summary of the results from the evaluation of the expanded set of alternatives is shown in Table 6-15. The results here are broken down into those from VIP Analysis and SMAA-2, and further disaggregated into the specific objective sets used in the analysis. All the results reflect the analysis with preference information.

The results from the VIP Analysis methodology for all three sets of objectives showed that the same alternative UNIMOD maintained the top ranking. Some rearranging of the following ranks from 2nd -5th was seen across the objective sets. DIVRSI fell to the 3rd and 4th positions in the ECOWAS and Dev-C sets respectively. LOCREC, which was ranked 4th in the ECOWAS+ evaluation, rose to 2nd and fell to 5th in the ECOWAS and Dev-C respectively.

The analysis within the SMAA-2 methodology found similar results across all three of the sets of EP objectives as shown in Table 6-15. UNIMOD and DIVRSII retained the top 2 ranks in the evaluation within the three EP objective sets. LOCREC remained in the 3rd ranked position, only falling to the 4th position making room for DIVRSIII, which was ranked 4th in the Dev-C evaluation. DIVRIII was ranked 9th in the ECOWAS+ and ECOWAS objective set evaluations, but became more attractive in the final Dev-C evaluation.

Overall, despite the expanded set of EP alternatives, no significant change was seen in the top ranked alternatives across the three sets of objective sets evaluated. UNIMOD remained attractive within both the VIP Analysis and SMAA-2 methodologies and all the EP objective sets. Some alterations in the rankings were seen within the VIP Analysis rankings for 2nd 3rd and 4th positions, however no significant changes were found in the set of alternatives that were considered attractive.

Table 6-15 - Alternatives in order of attractiveness - Expanded alternatives: Case Study

	VIP Analysis[1]			SMAA-2[2]		
Ranking	ECOWAS+	ECOWAS	Dev-C	ECOWAS+	ECOWAS	Dev-C
1	**UNIMOD***	**UNIMOD***	**UNIMOD***	**UNIMOD***	**UNIMOD***	**UNIMOD***
2	**DIVRSI**	**LOCREC***	DIVRSIII	**DIVRSII**	**DIVRSII**	**DIVRSII**
3	**DIVRSII**	**DIVRSI**	**DIVRSI**	**LOCREC***	**LOCREC***	**DIVRSIII**
4	**LOCREC***	**DIVRSII**	DIVRSII	DIVRSI	DIVRSI	**LOCREC***
5	YNGREN	YNGREN	**LOCREC***	HGMAIN*	YNGREN	DIVRSI
6	PRVREN	EXPREN*	YNGREN	YNGREN	HGMAIN*	HGMAIN*
7	EXPREN*	PRVREN	PRVREN	DSMREF	DSMREF	YNGREN
8	DSMREF	DSMREF	DSMREF	PRVREN	PRVREN	DSMREF
9	HGMAIN*	HGMAIN*	HGMAIN*	DIVRSIII	DIVRSIII	PRVREN
10	DIVRSIII	DIVRSIII	EXPREN*	STDALN	EXPREN*	LOWINV*
11	MNIGRD	MNIGRD	MNIGRD	MNIGRD	MNIGRD	EXPREN*
12	STDALN	STDALN	STDALN	LOWINV*	STDALN	MNIGRD
13	DIVPES*	DIVPES*	DIVPES*	EXPREN*	LOWINV*	STDALN
14	LOWINV*	LOWINV*	LOWINV*	LOWRUN*	LOWRUN*	LOWRUN*
15	LOWRUN*	LOWRUN*	LOWRUN*	DIVPES*	DIVPES*	DIVPES*

1. Sorted in order of value for max regret w/ min value as a "tie breaker". Non-dominated alternatives in Bold
2. Sorted in order of descending holistic acceptability indices. Alternatives with rank acceptabilty for R1 in Bold.
* "New" alternatives from the Expanded Alternatives set.

6.5 Sensitivity analysis

The main inputs to the evaluation model were the performances of the alternatives in the achievement of the EP objectives (presented in Table 6-10), and the constraints for the MCDA models (Section 6.3.2). Both of these (the performances and the constraints) had some uncertainties, and therefore could justify a sensitivity analysis. For the second however, the methods used to evaluate the alternatives, SMAA-2 and VIP Analysis, evaluate all possible weighting combinations given a set of constraints, which in the case of the current work consists of an ordinal ranking of the importance parameters of the attributes corresponding to the EP objectives. The conclusions do not depend on any vector of exact values for weights, and therefore a sensitivity analysis on these parameters was not needed. However, regarding the performance of the alternatives, it was deemed relevant to do such an analysis.

At this stage the sensitivity analysis consisted of establishing a method allowing variations in the performances of the alternatives in each of the attributes. This sensitivity analysis was performed to account for possible imprecisions in the data that fed the energy system model (Chapter 4), or of the energy system model itself.

For each of the seven attributes corresponding to the ECOWAS+ objective set a method to vary the performance of the alternative was established. The performance variation considered for each of the attributes is shown in Table 6-16. A description of each variation follows.

Table 6-16 - Performance variations for sensitivity analysis

	Attributes						
	1 PE Security	2 Adequacy of electricity generation	3 Maintainability of of electricity generation	4 Cost	5 Access to modern energy services	6 Impact on global climate	7 Impact on local Environment
Performance Variation	Min: - 50% Max: + 50%	Min: 75% Max: 100% of available Capacity	Constructed scale technology ratings varied. Min: -1 Max: +1	Max: +33%	No Variation	Max: + Calculated uncertainty[1] Min: - Calculated uncertainty[1]	Constructed scale technology ratings varied. Min: -1 Max: +1

[1]The min and max values for the alternatives are detailed in Table D- 15 in Appendix D

The variation of performance in PE diversity was assumed to have a maximum (max) and minimum (min) variation of 50% of the evaluated performance. This represented a large degree of uncertainty and allowed for an understanding of the considerable change in alternative rankings that may occur.

Attribute 2, evaluating the adequacy of the electricity generation, was varied based on the calculated available capacity for the respective alternative as the max (see Section 3.6.2.1), and the min calculated available capacity as 75% of the total calculated available capacity of the respective alternative. The performance of the alternative was then evaluated based on these max and min values. The value of 75% was based on a proxy value for SSA. Of total installed capacity in SSA, up to 25% of the total installed capacity was unavailable for reasons including lack of maintenance (Eberhard A. et al., 2008). This was an average value for the region however, and this can reach values of 40% of the total installed capacity, as was the case of unavailable installed capacity in Nigeria (Castellano et al., 2015).

For the maintainability of the FE supply system a change of the ratings assigned to the representative technologies was made to vary 1 level on the constructed scale, Table 3-5. This simulated a more conservative and less conservative evaluation on the maintainability of each technology.

The cost of the alternatives varied between the actual evaluated performance of the alternative and a max of 33% over the cost. The max value for the cost was taken as a proxy value for SSA. An analysis of SSA power-generation projects found that the projects had surpassed the budget by an average of 33% (Castellano et al., 2015).

No variations were considered in the access to modern energy as it is also an input to the model with repercussions in other attributes, as well as the model. Additionally, alternatives were constructed with varying levels of access to modern energy services, for example DIVRSIII, which reflect this variation.

For attribute 6, evaluating the impact on the global climate through the measure of CO_{2eq} emissions, the calculated uncertainty of the performance of the alternative was used to find the min and max following the procedure detailed in the IPCC (2000). The min and max values for the alternatives are detailed in Table D- 15 in Appendix D.

Variations of performance in attribute 7, evaluating the impact on local environment, a change of the ratings assigned to the representative technologies was made to vary 1 level on the constructed scale, Table 3-17. This simulated a more conservative, as well as a less conservative evaluation, on the local environmental impact of each technology.

6.5.1 Sensitivity analysis – Evaluation of expanded EP alternative set given variations in performance: SMAA-2

This sensitivity analysis consisted of an evaluation of the full set of alternatives within each of the three sets of EP objectives given variations in their performance. This was done both within SMAA-2 and VIP Analysis methodologies.

The rank acceptability indices of the expanded set of alternatives evaluated within the ECOWAS+ objective set, given variations in performance of the alternatives are shown in Figure 6-23.

Given variations in the performances of the alternatives it was obvious that there was a less clear winner, or most attractive alternative, and there was a more even distribution of the rank acceptability indices between the 15 ranks. This was opposed to an alternative having a dominating rank acceptability for a single rank. Additionally, each alternative had a more divided share of acceptable importance parameter vectors for a number of different rankings. With the variations of performance modeled in this work, a significant change in the rankings of attractive alternatives within all three objective sets was seen. This was due to the relatively large variations considered in this sensitivity analysis.

LOWINV, HGMAIN and LOWRUN were found to receive the top three holistic ranking positions. UNIMOD and DIVRSII fell from the top holistic rankings (see Section 3.9.2.5) to holistic rankings of the 5th and 6th positions, counting horizontally from the left most position. It is noted, however that the rank acceptability indices for the alternatives with the top six holistic rankings were relatively similar.

All 15 of the alternatives comprising the expanded alternative set received ranked acceptability for rank 1. The central weight vectors all had similar weights for the importance parameters following the ordinal ranking of the objectives for the ECOWAS+ set, varying only slightly among the alternatives. The central weight vectors for these alternatives evaluated within the ECOWAS+ objective set are shown in Figure D- 18 of Appendix D.

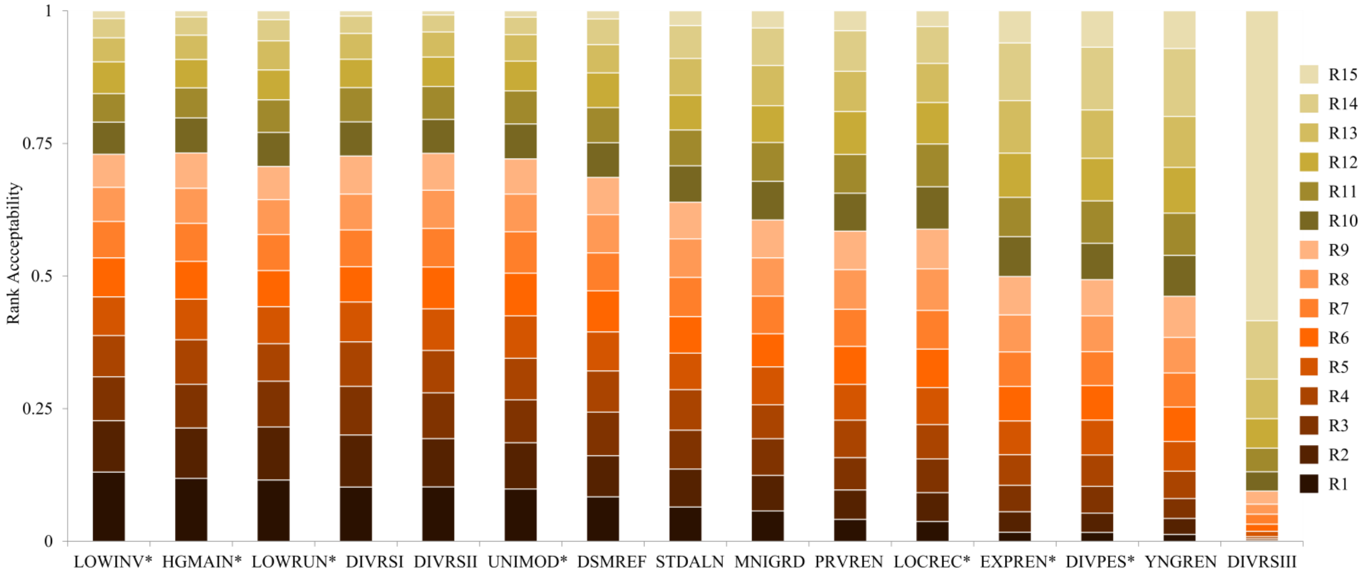

Figure 6-23 - Rank acceptabilities - ECOWAS+ objective set - Performance variations (Perf. var.): Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

The rank acceptability indices and the central weight vectors resulting from the evaluation of the alternatives given variation of the performances from the ECOWAS and Dev-C objective sets are presented in Figure D- 19 to Figure D- 20 and Figure D- 21 to Figure D- 22 of Appendix D, respectively.

The results from all three objective sets within the sensitivity analysis of performance variations are summarized for the SMAA-2 methodology in Table 6-18.

6.5.2 Sensitivity analysis - Evaluation of expanded EP alternative set given variations in performance: VIP Analysis

Following the analysis within SMAA-2, the alternatives were evaluated given the performance variations within VIP-Analysis.[22]

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[22] The sensitivity analysis conducted resulted in performance variations in the attributes which represented "extreme" variations in the performances of the evaluated alternatives. VIP Analysis does not natively have a method for variations in alternatives, instead the best case and worst case values were evaluated as separate alternatives.

The range of values resulting from the analysis of the ECOWAS+ set of EP objectives is shown in Figure 6-24. Here it is seen that given the large variations in performance the range of values that the alternatives may obtain became quite large spanning the majority of the range from 0 to 1. Alternatives LOCREC, UNIMOD, YNGREN, DIVRSI and DIVRSII were found to have maximum values close to 1, however all the alternatives were shown to have low minimum values in the evaluation.

Given the method employed to evaluate variations in performance within VIP Analysis, a confrontation table with non-dominated alternatives was not constructed. Instead, a ranking of the alternatives by the maximum value, minimum value and max regret was constructed and is shown in Table 6-17. Here it is seen that LOCREC, UNIMOD and YNGREN received the lowest max regrets and highest minimum values compared to the remaining alternatives. These results, however, did not differ greatly, in their actual relative value, in comparison to the remaining alternatives and so it would prove difficult to choose an attractive alternative from the set.

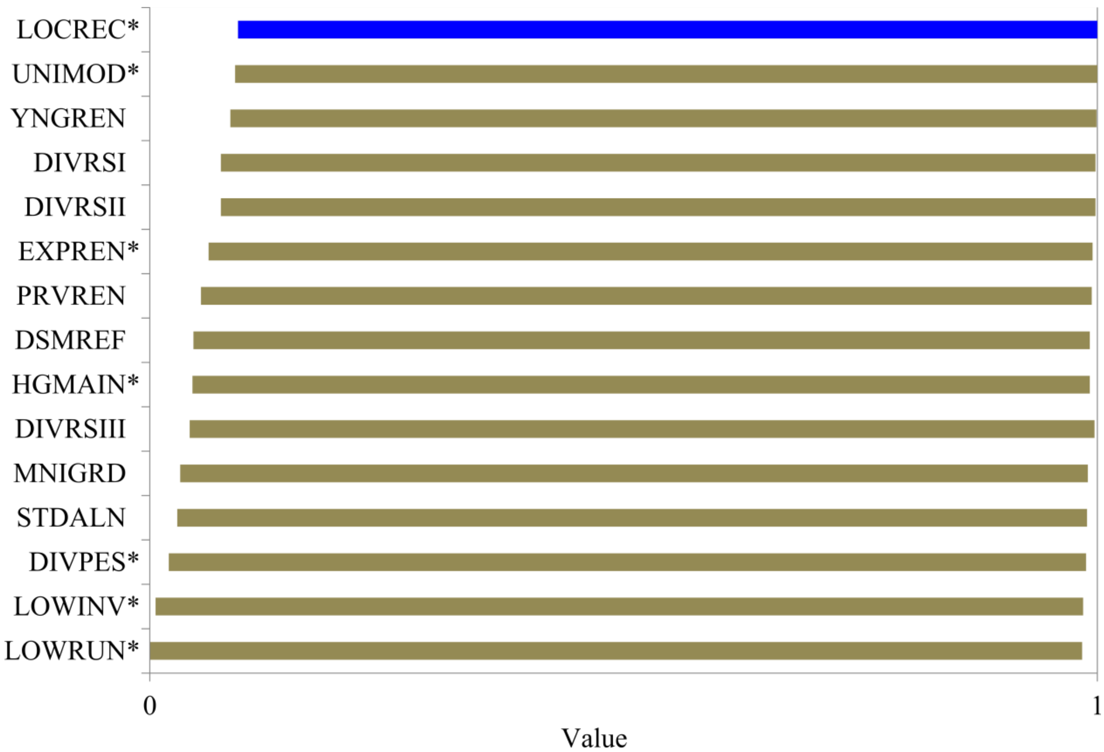

Figure 6-24 - Range of values - ECOWAS+ objective set - Perf. var.: Case study (“New” alternatives are distinguished by “ * ”)

The sensitivity analysis for performance variation results, from the ECOWAS and Dev-C objective sets in VIP Analysis, are presented in the Appendix D. The range of values for the ECOWAS set as well as the ranking of alternatives is shown in Figure D- 23 and Table D- 19 respectively. The range of values for the Dev-C set as well as the ranking of alternatives is shown in Figure D- 24 and Table D- 21 respectively. The results from all three objective sets are summarized below in Table 6-18.

Table 6-17 - Ranking of Alternatives- ECOWAS+ objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

	Max Value ranking of alternatives w/ variations in performance		**Min Value** ranking of alternatives w/ variations in performance		**Max Regret** ranking of alternatives w/ variations in performance	
Most	UNIMOD*	1.000	LOCREC*	0.093	LOCREC*	0.907
Attractive	LOCREC*	1.000	UNIMOD*	0.090	UNIMOD*	0.910
	YNGREN	0.999	YNGREN	0.085	YNGREN	0.915
	DIVRSI	0.998	DIVRSI	0.075	DIVRSI	0.925
	DIVRSII	0.998	DIVRSII	0.075	DIVRSII	0.925
	DIVRSIII	0.997	EXPREN*	0.062	EXPREN*	0.938
	EXPREN*	0.995	PRVREN	0.054	PRVREN	0.946
	PRVREN	0.994	DSMREF	0.046	DSMREF	0.954
	HGMAIN*	0.992	HGMAIN*	0.045	HGMAIN*	0.955
	DSMREF	0.992	DIVRSIII	0.042	DIVRSIII	0.958
	MNIGRD	0.990	MNIGRD	0.032	MNIGRD	0.968
	STDALN	0.989	STDALN	0.029	STDALN	0.972
↓	DIVPES*	0.988	DIVPES*	0.020	DIVPES*	0.980
Least	LOWINV*	0.985	LOWINV*	0.006	LOWINV*	0.994
Attractive	LOWRUN*	0.984	LOWRUN*	0.000	LOWRUN*	1.000

6.5.3 Summary of sensitivity analysis evaluation

A summary of the results from the sensitivity analysis allowing for variations in the performance of the alternatives is shown in Table 6-18. The results here are broken down into those from VIP Analysis and SMAA-2 and further disaggregated into the specific objective sets used in the analysis. All the results reflect the analysis with preference information.

No difference in the top two rankings for the three objective sets was found, which remained LOCREC and UNIMOD. The third ranked alternative, YNGREN, fell to a less attractive position in the Dev-C evaluation.

Within the SMAA-2 evaluation LOWINV remained the most attractive alternative in all three objective set evaluation frameworks. HGMAIN ranked 2nd in the ECOWAS+ evaluation dropped to 5th and 6th in the ECOWAS and Dev-C evaluations. DIVRSI, which was ranked 4th in the ECOWAS+ evaluation, was found to be more attractive in the ECOWAS and Dev-C evaluations.

Overall, given variations in the performance of alternatives little difference is seen among the different objective set evaluation frameworks both within VIP Analysis and SMAA-2.

The ranking of the alternatives here does not completely portray the close values that the alternatives received in the evaluations. An example would be the max regrets for LOCREC and UNIMOD within the VIP Analysis which were not considerably different. However, the alternatives are ranked 1st and 2nd implying a certain step down in attractiveness.

The same is true in rank acceptability indices resulting from the analysis in SMAA-2, given the variations in the performance as well as holistic acceptabilities of the alternatives. While considerable difference in the rank acceptabilities and holistic acceptabilities may not exist, the alternatives are ordered in Table 6-18 according to descending holistic acceptability indices.

Table 6-18 - Alternatives in order of attractiveness – Performance variations: Case Study

	VIP Analysis[1]			SMAA-2[2]		
Ranking	ECOWAS+	ECOWAS	Dev-C	ECOWAS+	ECOWAS	Dev-C
1	LOCREC*	LOCREC*	LOCREC*	**LOWINV***	**LOWINV***	**LOWINV***
2	UNIMOD*	UNIMOD*	UNIMOD*	**HGMAIN***	**DIVRSI**	**DIVRSI**
3	YNGREN	YNGREN	DIVRSI	**LOWRUN***	**DIVRSII**	**DIVRSII**
4	DIVRSII	DIVRSII	DIVRSII	**DIVRSI**	**LOWRUN***	**LOWRUN***
5	DIVRSI	DIVRSI	DIVRSIII	**DIVRSII**	**HGMAIN***	**DIVRSIII**
6	EXPREN*	EXPREN*	YNGREN	**UNIMOD***	**UNIMOD***	**HGMAIN***
7	PRVREN	PRVREN	EXPREN*	**DSMREF**	**DSMREF**	**UNIMOD***
8	DSMREF	DSMREF	PRVREN	**STDALN**	**LOCREC***	**DSMREF**
9	HGMAIN*	HGMAIN*	HGMAIN*	**MNIGRD**	**STDALN**	**STDALN**
10	DIVRSIII	DIVRSIII	DSMREF	**PRVREN**	**MNIGRD**	**LOCREC***
11	MNIGRD	MNIGRD	MNIGRD	**LOCREC***	**PRVREN**	**MNIGRD**
12	STDALN	STDALN	STDALN	**EXPREN***	**EXPREN***	**PRVREN**
13	DIVPES*	DIVPES*	DIVPES*	**DIVPES***	**DIVPES***	**EXPREN***
14	LOWINV*	LOWINV*	LOWINV*	**YNGREN**	**YNGREN**	**DIVPES***
15	LOWRUN*	LOWRUN*	LOWRUN*	**DIVRSIII**	**DIVRSIII**	**YNGREN**

1. Sorted in order of value for max regret w/ min value as a "tie breaker".
2. Sorted in order of descending holistic acceptability indices. Alternatives with rank acceptabilty for R1 in Bold.
* "New" alternatives from the Expanded Alternatives set.

6.6 Case study conclusions

The current chapter presented part II of the application of the national EP methodology, and specifically the decision support methodology, to the case study of Ghana.

The main objective of the current chapter was to produce results from the case study, which would aid in addressing the third and final research question of this work.

The set of alternatives developed in the previous Chapter 5, were evaluated within the framework of the three objective sets, ECOWAS+, ECOWAS and the Developed Country sets after eliciting preference information from DMs at a DC event in Ghana.

The evaluation of the first set of eight alternatives from the DC found no significant differences in the resulting attractive alternatives from the three sets of objectives (Section 6.3.6). The most attractive alternatives were common among all three objective sets as shown in Table 6-7 for both the VIP Analysis and SMAA-2 evaluations.

In order to further explore the decision space, the alternative set was expanded to 15 total alternatives, representing different energy policy pathways. This set of alternatives was evaluated in the first part of a sensitivity analysis.

With the additional alternatives the evaluation did not find substantial differences in the most attractive alternatives between the three objective sets as shown in Table 6-15 (Section 6.4.13). Slight variations were seen in the order of the 2^{nd} 3^{rd} and 4^{th} ranked alternatives, however the group of alternatives that held these ranks remained the same only moving up or down a rank.

For the sensitivity analysis the performance of the alternatives was varied for each of the attributes. The evaluation of the alternatives, given variations in performance, resulted in insignificant differences between the objective sets, as shown in Table 6-18 (Section 6.5.3). Again, the most attractive alternative was seen to maintain the 1^{st} ranking, and the 2^{nd} 3^{rd} and 4^{th} ranked alternatives were slightly reordered. However, the same group of alternatives maintained these ranks only moving up or down a rank. The alternatives were also found to be less comparable in the sensitivity analysis as there were no substantial differences in value.

No substantial differences in the attractiveness of the EP alternatives were identified given the evaluation within the three EP objective set frameworks. Slight changes in rank of a position or two positions were identified. Despite these changes in ranking the set of alternatives that comprised the top rankings did not show significant changes under each EP objective set framework (i.e. ECOWAS+, ECOWAS, and Developing countries).

The preferred EP alternatives, for all objective sets, consisted of a set of diverse actions, as shown in Table 6-7 and Table 6-15. Specifically, these were UNIMOD, DIVRSI, DIVRSII and LOCREC. This was opposed to less diversified alternatives and alternatives, with a singular focus, specifically YNGREN, PRVREN, LOWINV and LOWRUN.

These results will contribute to the conclusions drawn on the final research question of the work, which will be addressed along with the other conclusions in Chapter 7.

Chapter 7

Conclusions

This chapter presents the conclusions drawn from the current research, and is divided into five sections. In the first section, conclusions from the construction and use of the national energy system model are presented. In the second section the insights found in the case study conducted for the country of Ghana are discussed. In the third section conclusions are drawn for the research questions posed for the current work. In the fourth section the implications of the current work for future EP activities are reviewed. In the fifth and final section, future possible research topics are suggested.

7.1 Energy system model

A national energy supply and demand system model was constructed for application in the current work (as described in Chapter 4). This energy system model was well calibrated for the case study country of Ghana (detailed in Section 5.8).

Data availability for the case study country was an important concern in the construction of the energy system model and development of a reference projection for the planning horizon.

The availability of reliable data was a criteria used in the choice of the case study country, and as such, influenced the choice of Ghana, for the case study, from the 15 ECOWAS members. For the case study country, national level energy data was available from previous national EP efforts, and the agencies responsible for aggregation of energy data and EP efforts (i.e. the EC).

The data available for the case study country was found to be more comprehensive than the data available for the other ECOWAS members considered for the study. Data for total national PE resources, total national FE demand, and some disaggregation to total demand at the sector level was available.

Disaggregated data beyond the FE demand, by FE carrier type (e.g. electricity, fuelwood, gasoline, etc.), and at the FE demand sector level (e.g. Residential, Industry, Transports) was not available. No disaggregation of FE demand was available at subsector levels, such as

Road, Rail and Air transport or Passenger and Freight within the Transport FE demand sector. Additionally, a complete disaggregation of the shares, which specific FE services represented of FE demand within each demand sector, was not available. An example here was the share that lighting represented of FE demand for electricity in the Residential sector. In the absence of this disaggregation of FE demand, from the responsible energy data agencies, assumptions were required to be made.

Data at the end-use level may also be beneficial for energy modeling for DSM activities. End-use level data presents the useful energy needs such as "kWh/m^2 for cooling."

Beyond energy demand data, a set of complementary data was required to characterize the FE demand model. This complementary data was partially available for the case study country. First was the type of end-use technologies (e.g. lamps, furnaces, and boilers) used to convert FE, by carrier type (e.g. electricity, heat, and LPG), into the services that were actually in demand (e.g. lighting, heating, or cooking) and their respective conversion efficiencies. Next, the share that these end-use technologies represented in the mix of technologies used to provide each FE service was required. Finally, the household ownership levels of these technologies (i.e. appliances/household) were required to model the base year demand and to accurately portray projections of future FE demand. For the case study country, a catalog detailing of the end-use technologies used in the Residential and Service sectors was available. Data on the technologies used in the remaining FE demand sectors (i.e. Industry, Transport and Agriculture and Fishery), the shares that each technology represented in the end-use technologies used, and the ownership levels (for the Residential sector) were not available. In the absence of this complementary data, assumptions were required for the energy model.

The lack of disaggregation of data influenced the structure of the energy system model used. First it required the model to consist of a disaggregation of sector level FE demand to FE service level demand (and corresponding assumptions). The model stopped at the FE service level, and not at the end-use level, which would be beneficial for detailed DSM and energy efficiency planning efforts. Next, the lack of detailed data on the FE services represented in the demand sectors influences the understanding of the representative FE services that exist, the FE carriers that provide the services, and the end-use conversion technologies employed (e.g. appliances and respective efficiencies). This lack of data can be restrictive to the accuracy of energy modeling efforts, requiring assumptions about the FE services, their share in FE demand, the FE carriers utilized, and the end-use conversion technologies used.

7.2 Case study insights

The case study, applying the EP methodology in a real world application, provided insights into the energy supply and demand system and the planning considerations of Ghana, an ECOWAS member. Specifically, the case study provided an understanding of: (1) the structure of the energy sector of the country, (2) the preference information of energy sector actors, and (3) possible future sets of EP policy actions as represented by the constructed EP alternatives evaluated.

The case study provided the opportunity to apply the national energy system model to the energy system of Ghana. This provided a depiction of the PE resources, the PE conversion technologies (e.g. electricity generation and petroleum refining), the FE demand sectors, and finally the FE services represented in each sector.

The DC, conducted to evaluate the EP alternatives within a structured multicriteria evaluation activity, provided insights into the preferences of EP actors (e.g. the ranking of EP objectives) for energy sector planning activities.

Additionally, the DC allowed for the opportunity to evaluate a set of EP alternatives. The evaluation found that alternatives representing a diverse set of actions (e.g. combinations of actions such as transportation mode shifts, petroleum refining capacity, and DSM) as opposed to less diversified alternatives (e.g. focused primarily on low investment costs, low running costs, or use of renewables) were more attractive within all the evaluation structures used (e.g. EP objective sets).

The electricity generation requirements (installed capacity [MW]) in the Reference Projection of the current work were larger than those projected in the SNEP from the EC (2006a). This discrepancy in generation requirements resulted from a larger forecast of electricity demand along the planning horizon in the current work than that forecasted in the SNEP. Work from other authors has also previously presented FE demand and supply capacity requirements that exceeded that forecasted in the SNEP (Section 5.7.4.1).

It can be assumed that FE demand, inclusive of electricity, in Ghana will continue to grow due to population growth, increased access to electricity, and economic development. An underestimation of electricity may result in a gap between the actual demand and the supply (installed generation supply capacity). Furthermore, this gap may continue to widen as FE demand increases and supply capacity decreases due to ageing and/or unmaintainable units being taken out of commission. This widening gap would mean that the installed electricity generation capacity would be unable to meet electricity demand.

The power crises that Ghana has experienced during 2014 and 2015 may be evidence of this gap between supply and demand. Due to electricity demand exceeding supply capabilities, the national Electric Company of Ghana has had to implement rotational load shedding activities throughout the country. Additionally, the government has responded to the crises by establishing a new Ministry of Power, and ordering emergency power generators to supplement existing generation capacity (Republic of Ghana, 2014; Kpodo, 2015).

In addition to trying to ensure that adequate electricity supply is available for those with access to electricity, Ghana is facing the challenge of meeting the target of providing 100% access to electricity by 2020 (Detailed in Section 5.3.1). Granted that Ghana does meet this target and is able to bridge the gap between electricity supply and demand, there remains the relation between of electricity consumption per capita and economic development (Detailed in Section 1.1.1 and the relation to GDP/capita depicted in Figure 1-1). The electricity consumption per capita in Ghana for 2020 was, in the current work, calculated to reach 1,100 kWh/capita in the Reference projection.[23] This value was on the high end of the reported 2012 range of values from countries of SAA. It was however lower than that of South Africa which had a level of consumption at 4,039 kWh/capita in 2012. It was also significantly lower than industrialized countries such as the United States and Germany which had consumption levels of 12,070 kWh/capita and 6,523 kWh/capita in 2012 respectively (depicted in Figure 1-1) (US EIA, 2015a).

Due to the global risks that are posed by the effects of climate change, international commitment has focused on capping temperature rise at 2ºC, relative to pre-industrial levels, by 2100. To achieve this cap, international efforts have identified a per capita annual CO_{2eq} emissions goal of 2 tons CO_{2eq}/capita (IPCC, 2014; OGC, 2015).[24] Ghana, as a non-Annex I party of the United Nations Framework Convention on Climate Change (UNFCCC), is required to submit national communications detailing GHG inventories (UNFCCC, 2015). Following the Cancun Agreements, Ghana is also tasked with achieving a deviation in GHG emissions relative to the "business as usual" emissions in 2020 through nationally appropriate mitigation actions. As a non-Annex I party, however, it does not have to declare, or reach, any specific GHG reduction commitments (UNFCCC, 2010; Sharma and Desgain, 2013).

[23] Electricity consumption per capita was calculated with the forecast FE demand for electricity (provided by the national Grid, MiniGrid and Standalone systems) of the Reference Projection or EP alternative (Table 5-62 in Subchapter 5.10.9 and Table 6-9 of Subchapter 6.4.8), and the projection of population growth (presented in Figure 5-3 of Subchapter 5.4.1).

[24] This emissions goal is based the finding that 450ppm globally averaged CO_{2eq} concentration by 2100 is required to *likely* to maintain warming below 2ºC (IPCC, 2014). This would result in 1,800 $GtCO_{2eq}$ emissions for the century resulting in an average 18$GtCO_{2eq}$ per year for the century. Most recently, the Conference of the Parties (COP) in Paris emphasized that efforts should pursue a 1.5ºC cap, and this will affect annual emissions goals (UNFCCC - COP, 2015).

The GHG emissions per capita attributable to Ghana were projected to reach 8.9 CO_{2eq}/capita in 2020 for the Reference Projection in the current work.[25] The emissions per capita in 2020 for the Reference Projection, and all of the modeled alternatives, was significantly higher than the goal of 2 tons CO_{2eq}/capita goal by 2050. The alternatives with the maximum and minimum emissions per capita in 2020 were LOWINV and DIVSIII with 9.3 and 8.1 CO_{2eq}/capita respectively. LOWINV was an alternative based on a set of actions where electricity generation technologies with the lowest investment costs (i.e. gas turbines) were favored (detailed in Section 6.4.4). The DIVSIII alternative was an alternative based on a diverse set of actions considering DSM efforts and a mix of thermal and proven renewables for electricity generation; however universal access to electricity by 2020 was not assumed in this alternative (detailed in Section 5.10.8). Reducing CO_{2eq} emissions and achieving a 2050 emissions goal of 2 tons CO_{2eq}/capita would most likely take significant efforts on both the demand and supply side. Supply side efforts may consist, for example, of increased shares of renewable energy technologies in the electricity generation mix. Demand side efforts may include, for example, DSM activities within the specific FE demand sectors. Efforts will also have to include actions within the transportation sector in particular. These may include, for example, modal shifts from private to collective transport options, and/or shifts towards electric or alternatively fueled vehicles from the current petroleum based fuels.

7.3 Conclusions on the research questions

The research was structured around the three research questions posed for the current work (Section 1.2). The conclusions are presented in response to the questions.

> *Are there EP objectives specific to the local context that influence the successful implementation of energy plans?*

Two EP objectives specific to the local context that may influence the successful implementation of energy plans were identified in the context of the ECOWAS. These two objectives were to: (1) Maximize the maintainability of the FE supply system, and (2) Maximize the access to FE services (modern energy).

These two specific additional EP objectives were included in a set of seven EP objectives for EP in the ECOWAS region (ECOWAS+) comprising; (3) Maximize primary energy security, (4) Maximize the reliability of the FE system, (5) Minimize the costs (investment, operation &

[25] GHG emissions per capita were calculated with the performance of the Reference projection or EP Alternative on the EP objective to *Minimize Impact of Energy System on Global Climate* (detailed in Table 6-10 in Subchapter 6.4.9), and the projection of population growth (presented in Figure 5-3 of Subchapter 5.4.1).

maintenance), (6) Minimize the influence of the energy system on the global climate, and (7) Minimize the impact of the energy system on the local environment.

If these specific objectives exist, what quantifiable attributes can be employed to make them operational within the EP structure?

Quantifiable attributes were identified and/or constructed that allowed for these two EP objectives to become operational within the EP structure. A constructed scale attribute was developed to evaluate the maintainability of the FE supply system of EP alternatives. A constructed attribute was developed to evaluate the level of access that the population has to FE services within the EP alternatives (Details in Section 3.6).

Quantifiable attributes were also identified and/or constructed for the remaining EP objectives within the set of EP objectives for the ECOWAS. The quantifiable attributes, corresponding to the order of EP objectives (ECOWAS+) identified previously, consisted of attributes of: (3) PE diversity and import dependency, (4) Adequacy of electricity generation, (5) cost in monetary units of total investment, operation and maintenance of energy system, (6) CO_2 emissions, and (7) a constructed scale of local environmental impact of the FE system (Details in Section 3.6).

How do the results from an EP methodology including these additional objectives differ from those from one including solely the base objectives?

For the case study and alternatives analyzed, the EP methodology that incorporated additional EP objectives (ECOWAS+) did not make a considerable difference in the choice of the most preferable alternatives when compared with the results from other EP objective sets (i.e. ECOWAS and Developed Countries as discussed in Sections 6.3.6 and 6.4.13). The difference between the most preferable alternatives for the ECOWAS+ objective set and the ECOWAS set was less considerable than that between the ECOWAS+ and Developed Country set. However, the fact that the use of the context specific objectives (ECOWAS+) did not make a significant difference in this case, cannot be generalized as proof that it would not make a significant difference in any other case.

7.4 Implications

The work suggested implications and possible improvements that could make EP activities in the ECOWAS region more effective in the future.

It is likely that the findings of the literature review (Chapter 2), applicable to ECOWAS members, are representative of other developing countries. Firstly, adequate EP frameworks are required to support energy policy development and should be developed by responsible EP actors in the region. Secondly, energy master planning aids in policy development and avoidance of ad-hoc decision making. However, it was found to be largely absent from the national EP activities of ECOWAS members. Next, EP efforts in the region should identify fundamental objectives for the EP activity specific to the context of application. Additionally, EP activities should develop and evaluate multiple EP alternatives in contrast to the current practice of a single reference projection built in a future scenario. Finally, DMs should include the broad array of stakeholders in the EP activity to ensure ownership and responsibility of the plan to aid implementation.

The EP methodology developed in the current work may be of great assistance in addressing the issues raised in the preceding paragraph. The current work presented a methodology for EP at the national level in developing countries consisting of the three main activities of problem structuring, energy modeling and MCDA evaluation. An inclusive method of this type is novel for ECOWAS, and likely for other developing regions.

The literature review of EP activities in the ECOWAS region (Chapter 2) found that national EP activities were not being conducted by all of the ECOWAS member states. Additionally, comprehensive energy master planning activities (multiple PE resources, FE carriers and FE demand sectors) were not commonly conducted by ECOWAS members, and electricity system focused planning efforts were more common. This lack of comprehensive EP activities is possibly linked to the unavailability of data from the appropriate agencies responsible for data collection, and/or the absence of an agency responsible for this task. Efforts to ensure the collection of reliable energy sector data and a structure permitting responsible actors to utilize the data could be supportive of future EP and research activities in the ECOWAS region. The lack of energy sector related data (detailed in Section 7.1) can be restrictive to EP activities (i.e. national EP activities) and related research activities (i.e. the current work). Specific data requirements in need of improvement consist of: disaggregated FE demand at the sector and subsector levels for individual FE demand carriers; share of FE demand that individual FE services represent; useful energy needs for different FE services, the end-use technologies and their respective efficiencies; the share that different end-use technologies represent in the mix of employed technologies for each FE service; and household ownership levels of conversion technologies.

Addressing this lack of data, described in the previous paragraph, would be beneficial to ECOWAS members in the development of energy efficiency and renewable energy action plans. As discussed in Section 1.1.3, ECOWAS members, under the Energy Efficiency Policy and Renewable Energy Policy, are obligated to develop national action plans and measures in response to regional energy targets set for 2030 (ECREEE, 2013a).

As part of the work a procedure was provided, within the energy system model, to disaggregate the FE demand of the national energy balance into the FE services provided. This may be valuable for future efforts to disaggregate FE demand for EP activities in the case study country, or other possibly other countries in the region where disaggregated data is not available.

The work also presented a process to project the FE demand, at a disaggregated level, for the planning horizon, and the calculation of the respective required PE resources. This process may also be beneficial for future EP activities in the case study country or for other countries in the region conducting EP activities.

A methodology was developed, as part of the work, which supports the construction of multiple EP alternatives, representing policy actions, and the systematic evaluation of these EP objectives within a structured multicriteria evaluation framework. A methodology of this type was not found to be in use currently for EP activities in the region (Chapter 2). The methodology presented here may support future EP activities as it represents a structured and transparent method to develop and evaluate EP alternatives in achievement of stated EP objectives.

This methodology may also support future EP activities. The results from the case study do not suggest (1) that it would be critical to incorporate the specific EP objectives into the planning process of developing countries, nor (2) that they would significantly change the outcomes of EP activities. This is does not mean to imply that countries should not identify EP objectives specific to their application.

7.5 Future work

Future work to further disaggregate the national energy balance of a country in the region or other developing country to the end-use level would provide a deeper understanding of the energy system of the country and provide an additional level of energy data. This would support future EP activities considering DSM and energy efficiency measures. This work may also be supported by research aimed specifically at characterizing the energy end-uses of a country in the region, and the construction of a methodology for the collection and recording of data at this level to support future EP efforts.

Integration of alternative EP modeling software and/or approaches into the EP methodology proposed in the current work may be of interest for future work. The energy system model for this work was developed in the MATLAB environment, however there may be cases of application in which alternative EP modeling software or approaches would be beneficial. Future work could integrate currently available software packages (e.g. LEAP see Section 4.2.8) into the methodology for the development of the energy system model. LEAP, for example, has a user-friendly interface and supports the development of multiple alternatives and evaluation through a set of pre-defined attributes. The use of specific modeling software for minigrid and distributed energy systems considerations (e.g. Hybrid Optimization of

Multiple Energy Resources (HOMER)) may support the characterization of alternatives that detail the energy access considerations for these systems in rural areas (HOMER Energy, 2015).

Additional energy modeling approaches may also be beneficial to future EP efforts in developing countries. The current work focused on the development of a disaggregated bottom-up energy systems model, which was previously unavailable. Work to construct models following a top-down approach that establish a framework and assess the data requirements in the ECOWAS or for other developing regions (or countries), may also support future modeling efforts. An example of a top-down approach could include an econometric analysis of energy demand within the different energy demand sectors to establish a model and to project the FE demand.

Additional work could explore the use of alternative multicriteria evaluation methodologies for EP at different levels (e.g. regional (multi-nation), national or local). The current work adopted two methodologies that were identified as suitable for the activity, however other methodologies could prove beneficial in different applications. An example would be multi-objective programming methods in which a set of explicit objectives and constraints are declared and an alternative is chosen through the combination of different measures to identify efficient alternatives. This may aid in considering a comprehensive and diverse set of alternatives and thoroughly exploring the decision space.

Future work may include a further assessment of energy based indicators (Discussed in Section 2.6.5) and the proposal of a set of indicators, and a method to include these in EP activities, which would aid EP actors in the region with measurement and verification activities.

In discussions with energy sector actors attending the DC, as part of the case study, the relationship between the energy sector and the global climate was discussed. Energy sector actors expressed concern, not only of the impact of the energy sector on the global climate but also about the resiliency of the energy sector and possible adaptations that may be necessary in the context of the impacts of climate change, due to a large dependence on indigenous renewable PE resources (e.g. biomass, hydro, etc.) in developing countries of the region. Exploration of these concerns and the possible inclusion of them into the EP methodology may be beneficial for future EP efforts.

Development of a more interactive environment to use with participants within the DC setting would be advantageous. This interactive environment could take the form of a computer program(s) that is (are) comprehensive of the entire EP methodology proposed in the current work. This program would allow for the establishment of EP objectives and corresponding attributes, and employ a multicriteria evaluation methodology. Additionally, the program would support the interactive development of an energy system model and the construction of EP alternatives together with participants. Finally, the program would support the multicriteria evaluation of these alternatives with the participants of a DC. A program, or aid of this type, may further support the EP activity by presenting transparency in the methodology applied in the DC, and instilling ownership in the participants involved.

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Appendix A

Implementation factors literature review

References used in the review of factors for implementation.

Articles

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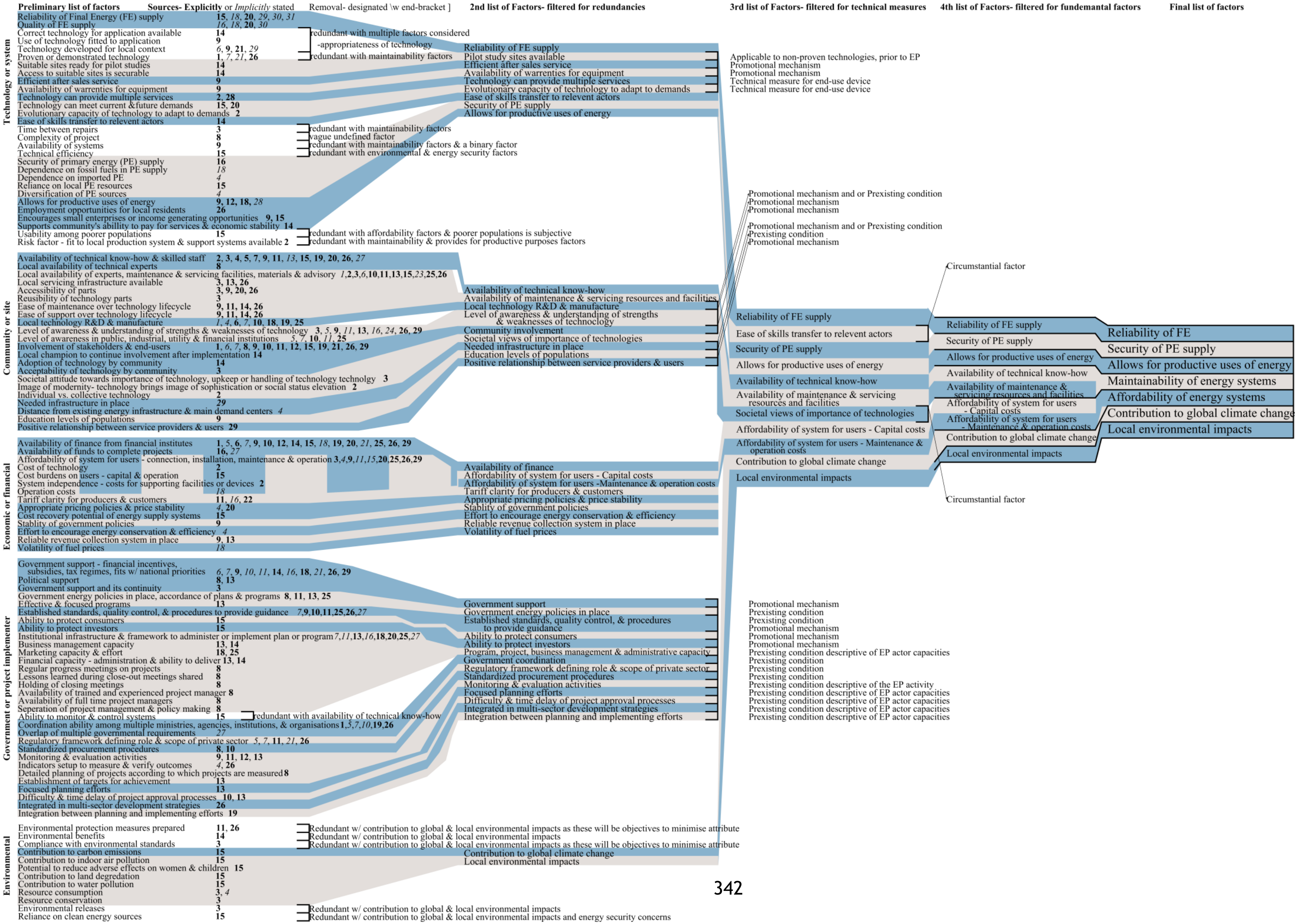


Figure A- 1 - Implementation factors filtering process

Appendix B

Mobility level- Transports

The measure of the activity level for the Transport sector is mobility which is measured in terms of the movement of passengers or freight over a unit of distance and has the units of passenger-km (pkm) or ton- km (tkm) respectively.

Data for the mobility in the Transport sector in Ghana for both passenger and freight mobility levels was not available or was limited in the literature and energy planning activities at the national level (EC, 2006d; MoT, 2011; World Bank, 2015a). The activity levels for the Transport sector were therefore calculated based on the available data and assumptions corresponding to each of the transport subsectors.

The mobility for each transport type within the individual subsectors was calculated on a general method based on the FE demand and assumptions on the vehicle types, efficiencies and the occupancy ratios. The method and disaggregation varies slightly based on the data available for each transport subsector. The mobility for each transport type was first totaled within each subsector and secondly for all subsectors to achieve the activity levels for pkm and tkm for the entire Transport sector.

B.1 -Road subsector

The road subsector activity level for the base year was calculated based on the FE demand for each of the transport types, assumptions on the mix of vehicle types, efficiencies, and average occupancy ratios as shown in Eq. B- 1. The calculated mobility levels for the road subsector are presented in Table B- 1 together with the occupancy levels and fuel efficiency values used.

$$Mobility_{s,i,y=0}^{road} = \frac{Q_{k,i,s,y=0}^{Tran}}{\eta_{k,i,s,y} \times e_i \times \rho_i \times 100} \times Use_{q,k,i,s,y} \quad [pkm\ or\ tkm] \qquad \textbf{Eq. B- 1}$$

Where:

$Mobility_{s,i,y=0}^{road}$: The activity for the road subsector, service *s* carrier *i* in year *y=0* *[pkm or tkm]*

$Use_{q,k,i,s,y}$: The use in occupancy (q=1) or load (q=2) for the subsector *k* service *s* carrier *i* in year *y* [pass/vehicle (veh) or ton/veh]

$\eta_{k,i,s,y}$: The energy efficiency of the vehicle for the subsector *k* service *s* carrier *i* in year *y* [l/100km]

e_i: Energy content of the FE carrier *i* [ktoe/ton]

ρ_i: Density of the FE carrier *i* [ton/l]

Table B- 1 – Road transport – Mobility and assumptions: Ghana 2008

Road	**Mobility [pkm]** ***Calculated***	Occupancy [pass/veh]	Energy efficiency [l/100km]	Reference
Passenger - Private				
Diesel	**1.88E+09**	1.4	9.0	(Anin et al., 2013; UITP and UATP, 2010)
Gasoline	**1.21E+10**	1.4	7.9	ibid.
LPG	**5.06E+08**	1.4	12.1	ibid.
Passenger - Collective Minibus "Trotro"				
Diesel	**5.57E+10**	18	11.7	ibid.
Gasoline	**7.86E+09**	18	11.7	ibid.
Large Bus				
Diesel	**3.93E+10**	68	31.3	ibid.
Gasoline	**5.55E+09**	68	31.3	ibid.
Taxi				
Diesel	**1.67E+09**	2.5[1]	9.0	(Anin et al., 2013)
Gasoline	**2.70E+08**	2.5	7.9	ibid.
LPG	**3.61E+09**	2.5	12.1	ibid.
Freight -LCV	**Mobility [tkm]**	Load factor [ton/veh]	Energy efficiency [l/100km]	
Diesel	**1.12E+09**	0.5	12.2	(Merven et al., 2012)
Gasoline	**2.00E+08**	0.5	14.2	ibid.
Freight -MCV				
Diesel	**1.14E+09**	2.5	30.0	ibid.
Gasoline	**1.83E+08**	2.5	38.7	ibid.
Freight -MHCV				
Diesel	**2.68E+09**	15	40.7	ibid.

1. Taxi occupancy assumed based on 2 taxi types – *Standard* where taxi takes 1-4 passengers and *Line* which only departs when 4 passengers arrive.

Table B- 2 – Transports - Energy content and density of FE carriers: Ghana

FE carrier	Energy content [toe/ton]	Density [ton/l]
LPG	1.08	0.00054
Diesel	1.02	0.00084
Gasoline	1.05	0.00075
Kerosene - aviation	1.03	0.00071

(EC, 2012a)

B.2 -Rail Subsector

National level data for the activity in the rail sector was available for the base year of 2008 from MOT (2011). This data for both the passenger and freight transport is shown in Table B- 3.

Table B- 3 - Rail transport - Mobility: Ghana 2008

Rail	Mobility [pkm]
Passenger	1.50E+07
	Mobility [tkm]
Freight	4.81E+07
(MoT, 2011)	

B.3 -Water-domestic

Data on the activity levels of domestic water transports was not available on the national level for Ghana. Data was, however available from the Volta River Authority, which runs the main domestic water ferry service on the Volta lake and its tributaries (MoT, 2011).

To estimate the activity level the annual passengers and tons of freight carried were used along with estimates of the distance of the two routes, north-south and east-west, which the company runs, and annual trips made as shown in Eq. B- 2.

The calculated activity and the number of passengers are presented in Table B- 4. The assumptions used in the calculation for the domestic water routes are shown in Table B- 5.

$$Mobility_{q,s,i,y=0}^{water} = Use_{q,k,i,s,y} \times \sum_{z}^{N} Share_{q,z} \times Dist_z \times Trip_z \quad [pkm\ or\ tkm] \qquad \textbf{Eq. B- 2}$$

Where:

$Mobility_{q,y=0}^{water}$: The annual mobility for type by mode in passengers, q=1, or load, q=2, in year *y [pkm or tkm]*

$Use_{q,k,y}$: Movement by mode *q* for the subsector *k* in year *y* [passengers or tons]

$Share_{q,z}$: Share of movement in route *z* and mode *q* [%]

$Dist_z$: Round trip distance for route *z* [km/trip]

$Trip_z$: Annual trips made on the route *z* [trip]

Table B- 4 - Water domestic transport – Mobility level and movement: Ghana 2008

Water - domestic	**Mobility [pkm]** ***Calculated***	Passengers [pass]
Passenger	**2.85E+11**	544,478
	Mobility [tkm] ***Calculated***	Load [tons]
Freight	**3.89E+10**	83,145

(MoT, 2011), calculations

Table B- 5 – Water domestic transport – Assumptions: Ghana 2008

Water – domestic Routes	Distance [km] *Estimate*[1]	Annual trips [trips/yr]	Share of passengers [%]	Share of freight [%]
North-South [Akosombo-Yeji]	522	104	4.51	16.00
East-West [Ferry crossing]	50	10,920	95.49	84.00

(MoT, 2011), calculations

1. Estimates based on round trip distance across lake and between destinations.

B.4 -Air domestic

The activity of the domestic air subsector was not available on the national level for the country of Ghana. The activity level was calculated based on assumptions regarding the number of domestic flights annually for all routes, the roundtrip distance and finally the total domestic passengers, Eq. B- 3.

The calculated activity for the subsector and the total passengers carrier and domestic flights are shown in Table B-6. The assumptions used in the calculation for the domestic air routes are shown in Table B- 7.

$$Mobility_{y=0}^{Air-dom} = Use_{k,y} \times Flights_y \times \sum_{z}^{N} Share_z \times Dist_z \quad [passkm] \qquad \textbf{Eq. B- 3}$$

Where:

$Mobility_{y=0}^{Air-dom}$: Mobility for the Air-domestic sector in year *y*

$Use_{k,y}$: Movement in passengers subsector *k* in year *y* [passengers]

$Flights_y$: Total trips made in year y [trip]

$Share_z$: Share of movement in route z [%]

$Dist_z$: Round trip distance for route z [km/trip]

Table B- 6 – Air domestic transport – Mobility and movement: Ghana 2008

Air - domestic	**Mobility [pkm]** ***Calculated***	Passengers [pass]	Flights [trips]
Passenger	**2.83E+11**	544,478	4,534

(GCAA, 2013a), calculations

Table B- 7 – Air domestic transport – Assumptions: Ghana 2008

Air- domestic Routes	Distance [km] *Estimate*[1]	Share of flights [%] *Estimate*[2]
Accra-Kumasi	382	39.0
Accra-Tamale	862	24.5
Accra-Takoradi	370	24.5
Accra-Sunyani	612	12.0

1. Based on round trip distance (FMT, 2015).
2. From share of weekly flights of domestic carrier (Antrak Air, 2015).

B.5 -Air-international

The level of activity for the base year for the case study country was not readily available in units of pkm or tons-km. The activity level was calculated based on assumptions regarding the number of international flights annually for all routes, the distance of the routes and finally the total international passengers as shown in Eq. B- 4. The international flights only consider the flights and passengers departing the country of Ghana as they are assumed to refuel at the international airport.

The calculated mobility for the subsector for both passenger and freight transport, total passengers and freight transported, and international departure flights are shown in Table B- 8. The assumptions used in the calculation for the international air routes are shown in Table B- 9.

$$Mobility_{q,y=0}^{Air-int} = Use_{k,q,y} \times Flights_y \times \sum_{z}^{N} Share_z \times Dist_z \quad [pkm\ or\ tkm] \qquad \textbf{Eq. B- 4}$$

Where:

$Mobility_{q,y=0}^{Air-int}$: Mobility level for the Air-international sector for mode type *q* in passengers, q=1, or load, q=2, in year y [$pkm\ or\ tkm$]

$Use_{k,q,y}$: Movement by mode *q* for the subsector *k* in year *y* [passengers or tons]

$Flights_y$: Total trips made in year y [trip]

$Share_{q,z}$: Share of movement in route *z* for movement type *q* [%]

$Dist_z$: Round trip distance for route z [km/trip]

Table B- 8 – Air international transport – Mobility and movement: Ghana 2008

Air - domestic	**Mobility [pkm]** ***Calculated***	Passengers [pass]	Flights [trips]
Passenger	**2.23E+13**	598,812	
	Mobility [tkm] ***Calculated***	Load [tons]	8,743
Freight	**1.22E+12**	32,706	

(EC, 2006d; GCAA, 2013b), calculations

Table B- 9 – Air international transport – Assumptions: Ghana 2008

Air- domestic Routes1	Distance [km] Estimate2	Share of flights [%] Estimate3
Accra-London	5,094	32
Accra-Lagos	412	24
Accra-Dubai	6,292	14
Accra-Nairobi	4,186	10
Accra-New York	8,245	9
Accra-Johannesburg	4,655	7
Accra-Cairo	4,270	4

1. Destinations assumed for Europe, West Africa, Middle East, N. America, S. Africa, & N. Africa (GCAA, 2013c, 2013d).
2. Based on round trip distance (FMT, 2015).
3. From share of passenger movement of domestic carrier (GCAA, 2013d).

Appendix C

Reference projection and Alternatives

Reference Projection

The electricity access assumptions are presented in Table C- 1 for new connections in the reference projection. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

Table C- 1 – Electricity access – Grid expansion assumptions – by HHS and connection type

Share of HHS connections [% of new household connections]													
Urban Grid connection	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CoreUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
PeriUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
Rural													
Grid	0	80	80	80	80	80	80	80	80	80	80	80	80
Minigrid	0	10	10	10	10	10	10	10	10	10	10	10	10
Standalone	0	10	10	10	10	10	10	10	10	10	10	10	10

Assumptions

The FE demand assumptions for the Reference Projection are presented in Sections 5.4 to 5.7. For the Residential sector these include the household ownership of appliances by FE service – carrier combination as well as the share of technologies in the end-use mix. For the productive sectors this includes the share of technologies in the end-use mix. The transportation sector is further detailed in Appendix B which includes the share which each transport type represents in the total mobility and corresponding transport technology type assumptions.

The electricity generation expansion plan is shown Table C- 2 for the planning horizon.

Table C- 2 - Electricity generation expansion plan -Reference Projection

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power								220	220	320	320	320	320	320
	CEN Power2								110	110	210	210	210	210	210
	Generic GT Plant 150MW + 100MW										150	250	250	250	250
CCGT	Tema		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di		0	110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2									210	360	360	360	360	360
	Generic Plant 60MW+60MW 1										60	60	60	60	60
	Generic Plant 450MW 1											225	450	450	450
	Generic Plant 450MW 2											225	450	450	450
	Generic Plant 450MW 3												225	450	450
	Generic Plant 450MW 4													225	450
	Generic Plant 450MW 5													225	450
	Generic Plant 450MW 6														225
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Generic Large Hydro 1										150	150	300	300	300
Wind	Generic Wind Farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind Farm 2											150	150	300	300
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
	Generic additional Landfills					1	2	3	4	5	6	7	8	9	10
Municipal Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20

	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants										20	40	60	80	100
Wood wastes	Generic wood wastes		3	3	3	3	3	3	3	3	3	4	4	4	15
Total		1,984	2,587	3,128	3,649	4,171	4,583	5,035	5,498	6,076	6,876	7,715	8,700	9,567	10,280

Alt. 1 PRVREN

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The FE demand assumptions are identical to those of the Reference Projection presented previously.

The electricity generation expansion plan is detailed in Table C- 3 for the planning horizon, and presented in Figure C- 1.

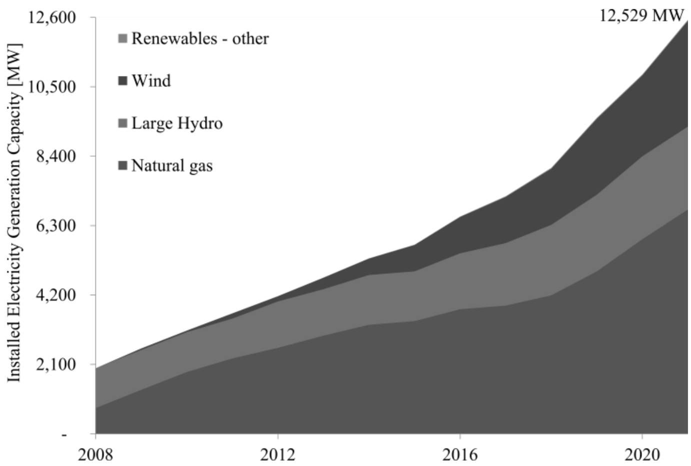


Figure C- 1 - Installed electricity generation capacity: Ghana Alt 1. PRVREN

Table C- 3 - Electricity generation expansion plan – Alt. 1 PRVREN

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power									220	220	320	320	320	320
	CEN Power2										110	110	210	210	210
	Generic GT Plant 150MW + 100MW 1													150	150

CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2											210	360	360	360
	Generic Plant 300MW 1												150	300	300
	Generic Plant 450MW 1												225	450	450
	Generic Plant 450MW 2													225	450
	Generic Plant 450MW 3													225	450
	Generic Plant 450MW 4													225	450
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Daboya Hydro													43	43
	Generic Large Hydro 1										150	150	300	300	300
	Generic Large Hydro 2											150	150	295	295
Wind	Wind farm		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 1						150	150	300	300	300	300	300	300	300
	Generic Wind farm 2							150	150	300	300	300	300	300	300
	Generic Wind farm 3								150	150	300	300	300	300	300
	Generic Wind farm 4									150	150	300	300	300	300
	Generic Wind farm 5										150	150	300	300	300
	Generic Wind farm 6											150	150	150	300
	Generic Wind farm 7												150	150	300
	Generic Wind farm 8												150	150	300
	Generic Wind farm 9												150	150	300
	Generic Wind farm 10													150	300
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Solar PV plant 3									2.5	5	5	5	5	5
	Generic Solar PV plant 4										2.5	5	5	5	5
	Generic Solar PV plant 5											2.5	5	5	5
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Total		1,984	2,584	3,125	3,646	4,166	4,729	5,311	5,724	6,576	7,189	8,048	9,561	11,100	12,529

Alt. 2 YNGREN

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The FE demand assumptions are identical to those of the Reference Projection presented previously.

The electricity generation expansion plan is detailed in Table C- 4 for the planning horizon and presented in Figure C- 2.

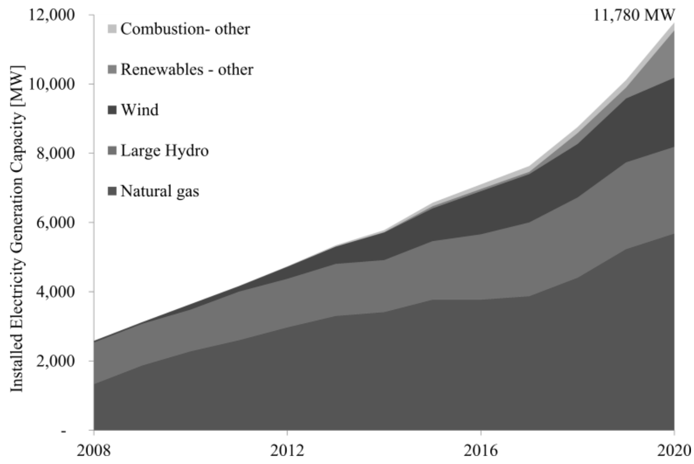


Figure C- 2 - Installed electricity generation capacity: Ghana Alt 2. YNGREN

Table C- 4 - Electricity generation expansion plan – Alt. 2 YNGREN

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power									220	220	320	320	320	320
CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT		0	110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2												210	360	360
	Generic Plant 450MW 1												225	450	450
	Generic Plant 450MW 2													225	450
	Generic Plant 450MW 3													225	450
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Daboya Hydro													43	43
	Generic Large Hydro 1										150	150	300	300	300
	Generic Large Hydro 2											150	150	295	295
Wind	Generic Wind farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 2						150	150	300	300	300	300	300	300	300
	Generic Wind farm 3							150	150	300	300	300	300	300	300
	Generic Wind farm 4								150	150	300	300	300	300	300
	Generic Offshore Wind farm 1										150	150	300	300	300
	Generic Offshore Wind farm 2											150	150	300	300

	Generic Offshore Wind farm 3													150	150
	Generic Offshore Wind farm 4														150
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Large Solar PV plant 1												200	200	400
Solar conc. thermal	Generic Concentrated Solar plant 1									50	50	50	50	50	50
	Generic Concentrated Solar plant 2												50	50	50
	Generic Concentrated Solar plant 3														50
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
	Generic additional Landfills					2	4	6	8	10	12	14	16	18	20
Mun. Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants										10	20	20	40	40
Wood wastes	Generic wood wastes	0	3	3	3	3	3	3	3	3	3	4	4	4	12
Marine wave	Generic Wave Power 1									200	200	200	200	200	200
	Generic Wave Power 2											200	200	200	200
Marine tidal	Generic Tidal Range Barrage Power 1										200	200	200	200	200
	Generic Tidal Range Barrage Power 2												200	200	200
Total		1,984	2,587	3,128	3,649	4,172	4,738	5,343	5,780	6,771	7,502	8,232	9,558	10,914	11,780

Alt. 3 MNIGRD

The electricity access assumptions are presented in Table C- 5 for new connections in the MNIGRD alternative. The shares of households connected follow the assumptions detailed previously for the MNIGRD alternative in Section 5.10.3 in which the minigrid option is favored for new connections.

Table C- 5 – Electricity access – Minigrid expansion assumptions – by HHS and connection type

Share of HHS connections [% of new household connections]													
Urban Grid connection	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CoreUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
PeriUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
Rural													
Grid	0	20	20	20	20	20	20	20	20	20	20	20	20
Minigrid	0	70	70	70	70	70	70	70	70	70	70	70	70
Standalone	0	10	10	10	10	10	10	10	10	10	10	10	10

Assumptions

The FE demand assumptions are identical to those of the Reference Projection presented previously.

The electricity generation expansion plan is detailed in Table C- 6 for the planning horizon and presented in Figure C- 3.

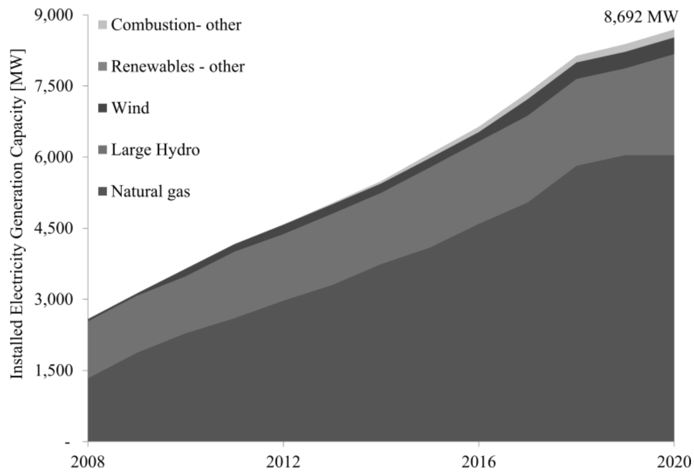


Figure C- 3 - Installed electricity generation capacity: Ghana Alt 3. MNIGRD

Table C- 6 - Electricity generation expansion plan – Alt. 3 MNIGRD

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power								220	220	320	320	320	320	320
	CEN Power2								110	110	210	210	210	210	210
	Generic GT Plant 150MW 1										150	150	150	150	150

CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2									210	360	360	360	360	360
	Generic Plant 450MW 1											225	450	450	450
	Generic Plant 450MW 2											225	450	450	450
	Generic Plant 450MW 3												225	450	450
	Generic Plant 450MW 4													225	450
	Generic Plant 450MW 5													225	225
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Generic Large Hydro 1										150	150	300	300	300
Wind	Generic Wind farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 2											150	150	150	150
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
	Generic additional Landfills											1	2	3	4
Municipal Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
Wood wastes	Generic wood wastes		3	3	3	3	3	3	3	3	3	4	4	4	4
Total		1,984	2,587	3,128	3,649	4,170	4,581	5,032	5,494	6,071	6,790	7,509	8,438	9,135	9,367

Alt. 4 STDALN

The electricity access assumptions are presented in Table C- 7 for new connections in the STDALN alternative. The shares of households connected follow the assumptions detailed previously for the STDALN alternative in Section 5.10.4 in which the standalone option is favored for new connections.

Table C- 7 – Electricity access – Standalone expansion assumptions – by HHS and connection type

Share of HHS connections [% of new household connections]													
Urban Grid connection	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CoreUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
PeriUrban													
Grid	0	100	100	100	100	100	100	100	100	100	100	100	100
Rural													
Grid	0	20	20	20	20	20	20	20	20	20	20	20	20
Minigrid	0	10	10	10	10	10	10	10	10	10	10	10	10
Standalone	0	70	70	70	70	70	70	70	70	70	70	70	70

Assumptions

The FE demand assumptions are identical to those of the Reference Projection presented previously.

The electricity generation expansion plan for the main grid is identical to that of Alt. 3 MNIGRD as described previously.

Alt. 5 DSMREF

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

As described in Section 5.10.5, the DSM considerations in the current alternative consist of energy conservation efforts restricted to FE demand for electricity. Energy conservation efforts in the current alternative are limited to interventions are made in the Residential, Service, and Agricultural and Fishery sectors through shifts in the end-use mix of appliances to more efficient alternatives.

Residential and Service sector DSM activities

The end-use mixes which reflect the DSM activities in the Residential sector for the current Alt. 5 DSMREF are shown in Table C- 8 to Table C- 15.

Table C- 8 – Residential - lighting technologies end-use mix: Alt. 5 DSMREF

Technology	Efficacy [Lumens/ Liter] & [Lumens/Watt]	Share in end-use mix [%]			
		2008	2012	2015	2020
Kerosene - [Lumens/ Liter]					
Kerosene wick lantern	0.13	70	70	70	70
Kerosene pressure lamp	0.99	30	30	30	30
Electricity - [Lumens/Watt]					
Incandescent lamp (100 Watt)	12.00	34	11	0	0
Fluorescent F40T12 4' 34W + magnetic ballast system	80.00	65	29	0	0
Fluorescent F32T8 4' 32W + electronic ballast system	90.00	0	22	40	46
Fluorescent F28T5 4' 28W + electronic ballast system	100.00	0	14	23	16
CFL	67.00	1	24	30	26
LED lamp	94.00	0	0	5	9
LED tube lamp	100.00	0	0	3	4

References: (Constantine et al., 1999; EC, 2004; Schwarz et al., 2005; EC, 2006d; LRC, 2015)

Table C- 9 – Residential - water heating technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [%]	Share in end-use mix [%]			
		2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	27.0	20.0	10.0
Improved fuelwood stove	32.5	5.0	27.0	20.0	75.0
Traditional mud stove	17.5	60.0	47.0	59.0	15.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	75.0	58.0	46.0	25.0
Improved stove	34.5	25.0	42.0	54.0	75.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	100.0	100.0	100.0	100.0
Insulated storage-tank heater	92.0	0.0	0.0	0.0	0.0
Electricity- [Energy Efficiency Index]					
Emersion heater - 1500W	13.0	37.0	17.0	2.0	0.0
Kettle-2000W	13.0	37.0	17.0	2.0	0.0
Instant flow heater -4000W	97.0	5.0	7.0	9.0	11.0
Solar heater - 175liter storage tank	188.1	2.0	5.0	7.0	10.0
Insulated tank heater - Class G	26.0	20.0	16.0	13.0	8.0
Insulated tank heater - Class F	28.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class E	32.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class D	35.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class C	43.5	0.0	19.0	34.0	11.0
Insulated tank heater - Class B	62.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A	95.0	0.0	12.0	21.0	36.0
Insulated tank heater - Class A+	132.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A++	169.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class A+++	188.1	0.0	8.0	14.0	24.0

References: (EC, 2004, 2006d; European Commission, 2013; DOE, 2015; EPA, 2015) assumptions

Table C- 10 - Residential - refrigeration technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [Energy Efficiency Index]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Refrigerator[1] prior to regulation	100.0	80.0	40.0	10.0	0.0
1 Star refrigerator	95.0	10.0	8.0	6.5	4.0
2 Star refrigerator	82.5	10.0	8.0	6.5	4.0
3 Star refrigerator	65.0	0.0	24.0	42.0	32.0
4 Star refrigerator	48.5	0.0	12.0	21.0	36.0
5 Star refrigerator	41.0	0.0	8.0	14.0	24.0

1. All are assumed to be combined Refrigerator +Freezer

References: (EC, 2004, 2006d; MoE, 2009b)

Table C- 11 - Residential - freezing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [Energy Efficiency Index]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Freezer Prior to regulation	100.0	80.0	40.0	10.0	0.0
1 Star rated Freezer	95.0	10.0	8.0	6.5	4.0
2 Star rated Freezer	82.5	10.0	8.0	6.5	4.0
3 Star rated Freezer	65.0	0.0	24.0	42.0	32.0
4 Star rated Freezer	48.5	0.0	12.0	21.0	36.0
5 Star rated Freezer	41.0	0.0	8.0	14.0	24.0

References: (EC, 2004, 2006d; MoE, 2009b)

Table C- 12 – Residential - air-conditioning technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Low EER[1] AC	2.25	90	50	20	0
Minimum EER AC	2.8	10	18	24	34
High EER AC	3.5	0	12	21	36
Highest EER AC	4.1	0	20	35	30

1. All AC units are assumed non ducted of various sizes

References: (Constantine et al., 1999; EC, 2004, 2006d; Hierzinger and Krivošík, 2012; EC, 2015a)

Table C- 13 – Residential – clothes washing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	87.0	100.0	60.0	30.0	0.0
Class C appliance	82.0	0.0	10.0	8.5	6.0
Class B appliance	72.5	0.0	8.0	14.0	24.0
Class A appliance	63.5	0.0	18.0	40.5	58.0
Class A+ appliance	55.5	0.0	0.0	0	0.0
Class A++ appliance	49.0	0.0	4.0	7.0	12.0

References: (EC, 2006d; European Commission, 2010a)

Table C- 14 – Residential - dishwashing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	91.0	100.0	60.0	30.0	0.0
Class C appliance	85.0	0.0	10.0	8.5	6.0
Class B appliance	75.5	0.0	8.0	14.0	24.0
Class A appliance	67.0	0.0	18.0	40.5	58.0
Class A+ appliance	59.5	0.0	0.0	0	0.0
Class A++ appliance	53.0	0.0	4.0	7.0	12.0

References: (de Bruyn and Opschoor, 1997; EC, 2006d; FSEC, 2008; European Commission, 2010b)

Table C- 15 - Residential - cooking technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	27.0	20.0	10.0
Improved fuelwood stove	32.5	5.0	27.0	20.0	75.0
Traditional mud stove	17.5	60.0	47.0	59.0	15.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	75.0	58.0	46.0	25.0
Improved stove	34.5	25.0	42.0	54.0	75.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	70.0	66.0	63.0	58.0
LPG Stove-cooker/oven	57.5	30.0	34.0	37.0	42.0
LPG Metal cabinet oven	57.5	0.0	0.0	0.0	0.0

References: (EC, 2004, 2006d)

The end-use mixes which reflect the DSM activities in the Service sector for the current Alt. 5 DSMREF are shown in Table C- 16 to Table C- 23.

Table C- 16 – Service lighting technologies end-use mix: Alt. 5 DSMREF

Technology	Efficacy [Lumens/ Liter] & [Lumens/Watt]	Share in end-use mix [%] 2008	2012	2015	2020
Kerosene - *efficiency*					
Kerosene wick lantern	0.345	70	70	70	70
Kerosene pressure lamp	0.687	30	30	30	30
Electricity - *power*					
Incandescent lamp	100	34	11	0	0
Fluorescent F40T12 4’ 34W + magnetic ballast system	48	65	29	0	0
Fluorescent F32T8 4’ 32W + electronic ballast system	40	0	22	40	46
Fluorescent F28T5 4’ 28W + electronic ballast system	32.2	0	14	23	16
CFL	23	1	24	30	26
LED lamp	17	0	0	5	9
LED 4' lamp	22	0	0	3	4

References: (Constantine et al., 1999; EC, 2004, 2006d)

Table C- 17 – Service - water heating technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [%]	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	27.0	20.0	10.0
Improved fuelwood stove	32.5	5.0	27.0	20.0	75.0
Traditional mud stove	17.5	60.0	47.0	59.0	15.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	75.0	58.0	46.0	25.0
Improved stove	34.5	25.0	42.0	54.0	75.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	100.0	100.0	100.0	100.0
Insulated storage-tank heater	92.0	0.0	0.0	0.0	0.0
Electricity- [Energy Efficiency Index]					
Emersion heater - 1500W	13.0	37.0	17.0	2.0	0.0
Kettle-2000W	13.0	37.0	17.0	2.0	0.0
Instant flow heater -4000W	97.0	5.0	7.0	9.0	11.0
Solar heater - 175liter storage tank	188.1	2.0	5.0	7.0	10.0
Insulated tank heater - Class G	26.0	20.0	16.0	13.0	8.0
Insulated tank heater - Class F	28.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class E	32.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class D	35.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class C	43.5	0.0	19.0	34.0	11.0
Insulated tank heater - Class B	62.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A	95.0	0.0	12.0	21.0	36.0
Insulated tank heater - Class A+	132.5	0.0	0.0	0.0	0.0
Insulated tank heater - Class A++	169.0	0.0	0.0	0.0	0.0
Insulated tank heater - Class A+++	188.1	0.0	8.0	14.0	24.0

References: (EC, 2004, 2006d; European Commission, 2013; DOE, 2015; EPA, 2015) assumptions

Table C- 18 - Service - refrigeration technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [Energy Efficiency Index]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Refrigerator[1] prior to regulation	100.0	80.0	40.0	10.0	0.0
1 Star refrigerator	95.0	10.0	8.0	6.5	4.0
2 Star refrigerator	82.5	10.0	8.0	6.5	4.0
3 Star refrigerator	65.0	0.0	24.0	42.0	32.0
4 Star refrigerator	48.5	0.0	12.0	21.0	36.0
5 Star refrigerator	41.0	0.0	8.0	14.0	24.0

1. All are assumed to be combined Refrigerator +Freezer
References: (EC, 2004, 2006d; MoE, 2009b)

Table C- 19 - Service - freezing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [Energy Efficiency Index]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Freezer Prior to regulation	100.0	80.0	40.0	10.0	0.0
1 Star rated Freezer	95.0	10.0	8.0	6.5	4.0
2 Star rated Freezer	82.5	10.0	8.0	6.5	4.0
3 Star rated Freezer	65.0	0.0	24.0	42.0	32.0
4 Star rated Freezer	48.5	0.0	12.0	21.0	36.0
5 Star rated Freezer	41.0	0.0	8.0	14.0	24.0

References: (EC, 2004, 2006d; MoE, 2009b)

Table C- 20 – Service - air-conditioning technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Low EER[1] AC	2.25	90	50	20	0
Minimum EER AC	2.80	10	18	24	34
High EER AC	3.50	0	12	21	36
Highest EER AC	4.10	0	20	35	30

1. All AC units are assumed non ducted of various sizes
References: (Constantine et al., 1999; EC, 2004, 2006d; Hierzinger and Krivošík, 2012; EC, 2015a)

Table C- 21 – Service – clothes washing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	87.0	100.0	60.0	30.0	0.0
Class C appliance	82.0	0.0	10.0	8.5	6.0
Class B appliance	72.5	0.0	8.0	14.0	24.0
Class A appliance	63.5	0.0	18.0	40.5	58.0
Class A+ appliance	55.5	0.0	0.0	0	0.0
Class A++ appliance	49.0	0.0	4.0	7.0	12.0

References: (EC, 2006d; European Commission, 2010a)

Table C- 22 – Service - dishwashing technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency [EER rating]	Share in end-use mix [%] 2008	2012	2015	2020
Electricity					
Class D appliance	91.0	100.0	60.0	30.0	0.0
Class C appliance	85.0	0.0	10.0	8.5	6.0
Class B appliance	75.5	0.0	8.0	14.0	24.0
Class A appliance	67.0	0.0	18.0	40.5	58.0
Class A+ appliance	59.5	0.0	0.0	0	0.0
Class A++ appliance	53.0	0.0	4.0	7.0	12.0

References: (de Bruyn and Opschoor, 1997; EC, 2006d; FSEC, 2008; European Commission, 2010b)

Table C- 23 - Service - cooking technologies end-use mix: Alt. 5 DSMREF

Technology	Efficiency	Share in end-use mix [%] 2008	2012	2015	2020
Fuelwood					
3-Stone fuelwood stove	15.5	35.0	27.0	20.0	10.0
Improved fuelwood stove	32.5	5.0	27.0	20.0	75.0
Traditional mud stove	17.5	60.0	47.0	59.0	15.0
Sawdust stove	26.2	0.0	0.0	0.0	0.0
Charcoal					
Traditional stove -*Coal pot*	21.0	75.0	58.0	46.0	25.0
Improved stove	34.5	25.0	42.0	54.0	75.0
Ceramic stove - *Jiko*	45.2	0.0	0.0	0.0	0.0
LPG					
Tabletop stove	57.5	70.0	66.0	63.0	58.0
LPG Stove-cooker/oven	57.5	30.0	34.0	37.0	42.0
LPG Metal cabinet oven	57.5	0.0	0.0	0.0	0.0

References: (EC, 2004, 2006d)

Petroleum refining

Within the current alternative the refinery capacity is increased following the additions to the TOR as described in Section 5.10.5. The total capacity of TOR as well as the annual capacity by product, for the planning horizon, are shown in Table C- 24. The annual capacity by product is based on the shares of products of the refinery as presented previously in Section 4.7.3, Petroleum refining, and assumed constant throughout the planning horizon.

Table C- 24 - Petroleum refining capacity – Alt. 5 DSMREF

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total Capacity [b/d]	29,736	59,736	59,736	59,736	74,736	74,736	74,736	74,736	74,736	74,736	99,736	99,736	99,736
Annual capacity by product [ktoe/yr]													
Diesel	217	389	389	389	474	474	474	474	474	474	617	617	617
Gasoline	97	173	173	173	211	211	211	211	211	211	275	275	275
Kerosene	635	1,135	1,135	1,135	1,384	1,384	1,384	1,384	1,384	1,384	1,801	1,801	1,801
LPG	476	850	850	850	1,037	1,037	1,037	1,037	1,037	1,037	1,349	1,349	1,349
Refined fuel oil	54	97	97	97	118	118	118	118	118	118	154	154	154
Losses	95	170	170	170	207	207	207	207	207	207	269	269	269

References: (EC, 2006c)
1. At 78% operating capacity
2. Gasoline and gasoline premix
3. Aviation turbine & general kerosene
4. Losses, consumption &/or non-fuel outputs

The electricity generation expansion plan is detailed in Table C- 25 for the planning horizon and presented in Figure C- 4.

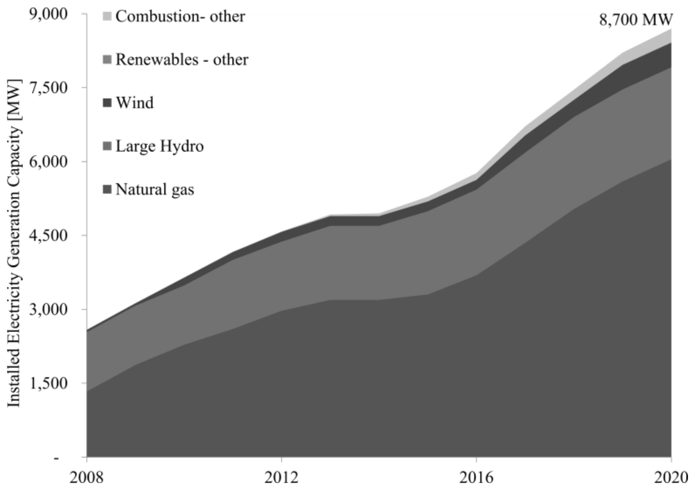


Figure C- 4 - Installed electricity generation capacity: Ghana Alt 5. DSMREF

Table C- 25 - Electricity generation expansion plan – Alt. 5 DSMREF

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power										220	320	320	320	320
	CEN Power2												110	220	220
	Generic GT Plant 150MW +100MW 1											150	250	250	250
CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2									110	220	360	360	360	360
	Kpone turbine 2											210	360	360	360
	Generic Plant 60MW + 60MW 1										60	120	120	120	120
	Generic Plant 450MW 1												225	450	450
	Generic Plant 450MW 2													225	450
	Generic Plant 450MW 3														225
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
Wind	Generic Wind farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 2											150	150	300	300
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
	Generic additional Landfills					1	2	3	4	5	6	7	8	9	10
Municipal Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)									0	20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants									0	20	40	60	80	100
Wood wastes	Generic wood wastes		3	3	3	3	3	3	3	3	3	4	4	4	15
Total		1,984	2,587	3,128	3,649	4,171	4,583	4,925	4,948	5,286	5,766	6,715	7,460	8,212	8,700

Alt. 6 DIVRSI

The electricity access assumptions are identical to those of the MNIGRD alternative as presented previously in Table C- 5 for new connections. The shares of households connected follow the assumptions detailed previously for the MNIGRD alternative in Section 5.10.3 in which the MNIGRD option is favored for new connections.

Within the current alternative the refinery capacity is increased following the additions to the TOR as described previously for the DSMREF alternative in Table C- 24.

The electricity generation expansion plan is detailed in Table C- 26 for the planning horizon and presented in Figure C- 5.

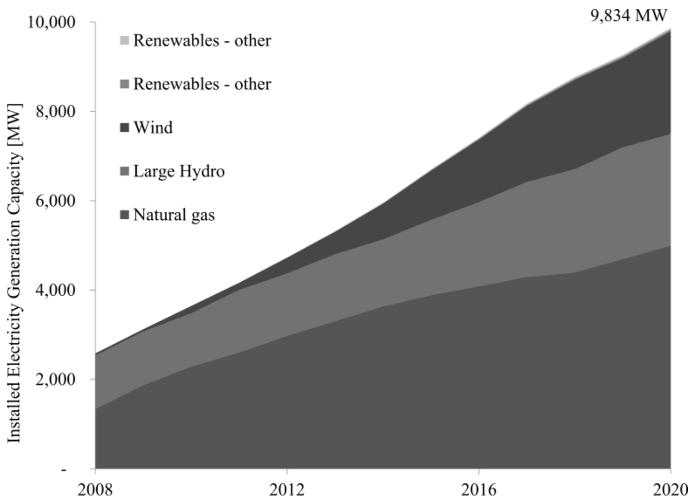


Figure C- 5 - Installed electricity generation capacity: Ghana Alt 6. Diverse actions I

Table C- 26 - Electricity generation expansion plan – Alt. 6 DIVRSI

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power								220	220	320	320	320	320	320
	CEN Power2									110	210	210	210	210	210
	Generic GT Plant 150MW 1														150
CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2											210	210	360	360
	Generic Plant 300MW 1													150	300
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Daboya Hydro													43	43
	Generic Large Hydro 1										150	150	300	300	300
	Generic Large Hydro 2											150	150	295	295
Wind	Generic Wind farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 2						150	150	300	300	300	300	300	300	300
	Generic Wind farm 3							150	150	300	300	300	300	300	300
	Generic Wind farm 4								150	150	300	300	300	300	300
	Generic Wind farm 5									150	150	300	300	300	300
	Generic Wind farm 6										150	150	300	300	300
	Generic Wind farm 7											150	150	150	300
	Generic Wind farm 8												150	150	300
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Solar PV plant 3									2.5	5	5	5	5	5
	Generic Solar PV plant 4										2.5	5	5	5	5
	Generic Solar PV plant 5											2.5	5	5	5
	Generic Solar PV plant 6												2.5	5	5
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Total		1,984	2,584	3,125	3,646	4,166	4,729	5,311	5,944	6,686	7,389	8,148	8,739	9,230	9,834

Alt. 7 DIVRSII

The electricity access assumptions are identical to those of the MNIGRD alternative as presented previously in Table C- 5 for new connections. The shares of households connected follow the assumptions detailed previously for the MNIGRD alternative in Section 5.10.3 in which the MNIGRD option is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

Within the current alternative the refinery capacity is increased following the additions to the TOR as described previously for the DSMREF alternative in Table C- 24.

The electricity generation expansion plan for the main grid is identical to that of Alt. 6 DIVRSI as described previously.

Transportation

With the completion of the "Western Railway Project" it is assumed that policy efforts will promote a shift in passenger and freight transport towards rail transport. The shift will include both collective and private road transport of all fuel types as well as freight transport of all categories, e.g. medium and heavy, and fuel types as described previously in Section 5.10.7. By 2020 10% of private and collective passenger transport, 5% of passenger taxi transport, and 20% of freight transport to were assumed to shift to collective and freight rail transport. The considerations are presented below.

The reduction in road sub-sector transport mobility for both passengers and freight for all modal types and FE carriers are shown in Table C- 27. The reduction is presented as share in respect to the reference projection. The difference in the share represents a shift in mobility to rail transport, and so all reduced mobility in pkm or tkm seen in Table C- 27 is reflected in increased mobility in the rail transport sub-sector for pkm or tkm respectively.

Table C- 27 – Reduction in Road transport mobility: Alt. 7 DIVRSII

Mobility relative to base year [-] **Road**	**2008**	**2012**	**2015**	**2020**
Passenger - Private				
Diesel	1	0.989	0.981	0.967
Gasoline	1	0.989	0.981	0.967
LPG	1	0.989	0.981	0.967
Passenger - Collective				
Minibus "Trotro"				
Diesel	1	0.983	0.971	0.950
Gasoline	1	0.983	0.971	0.950
Large Bus				
Diesel	1	0.983	0.971	0.950
Gasoline	1	0.983	0.971	0.950
Taxi				
Diesel	1	0.998	0.996	0.993
Gasoline	1	0.998	0.996	0.993
LPG	1	0.998	0.996	0.993
Freight -LCV				
Diesel	1	0.990	0.973	0.943
Gasoline	1	0.990	0.973	0.943
Freight -MCV				
Diesel	1	0.990	0.973	0.943
Gasoline	1	0.990	0.973	0.943
Freight -MHCV				
Diesel	1	0.990	0.973	0.943

Assumptions

Alt. 8 DIVRSIII

The assumptions for new electricity access connections are identical to those of the Reference Projection alternative as presented previously in Table C- 1 for new connections. Electricity access efforts are assumed to be delayed resulting in a share of 90% of the population with access at the end of the planning horizon.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

Within the current alternative the refinery capacity remains unchanged following the Reference Projection.

The electricity generation expansion plan for the main grid is identical to that of Alt. 6 DIVRSI as described previously.

Alt. 9 UNIMOD

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected to electricity follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The UNIMOD alternative however differs from the Reference Projection as LPG access rates reach 100% by 2020 as described previously in Section 6.4.1. The FE access rates are shown below in Table C- 28 for the current alternative.

Table C- 28 – Energy access rate assumptions: Ghana 2008 – 2020 – Alt. 9 UNIMOD

Access rate [% of households]		Year			
FE carrier	Population type	2008	2012	2015	2020
Fuelwood	CoreUrban	100	100	100	100
	PeriUrban	100	100	100	100
	Rural	100	100	100	100
Charcoal		80	80	80	80
		80	80	80	80
		76	76	76	76
Kerosene		100	100	100	100
		90	90	90	90
		80	80	80	80
LPG		35	56	73	100
		20	47	67	100
		3	35	59	100
Electricity		86	90	94	100
		86	90	94	100
		55	70	81	100

References: (EC, 2006a) Assumptions

The current alternative assumes provision of 100% access of electricity and LPG. The Residential sector undergoes a 100% shift away from fuelwood and charcoal for cooking and water heating to services provided by electricity and LPG. In addition, a 100% shift to electricity for lighting is made from the previous mix which included kerosene lighting technologies. Additional DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

To model the shift from traditional FE to modern FE carries for cooking and water heating the useful energy needs for these services were required. The model built for the national energy system of Ghana was limiting in the fact that it stopped at the level of FE intensity, and not the useful energy needs. This is because the model was not intended for a detailed DSM modeling activity.

The model allows for shifts in the end-use technology mix within each technology and carrier combination, e.g. a shift to improved fuelwood cookstoves from traditional less efficient cookstoves. The model, however, did not allow for shifts in demand from one technology and carrier combination to another, e.g. shift in water heating from fuelwood stoves to LPG insulated storage tank heaters.

To overcome this limitation in the current alternative the useful energy needs were calculated based on the FE demand intensity and the end-use technology mix for each of the technology and carrier combinations. The calculated useful energy needs for cooking, water heating and lighting for each of the population types is shown in Table C- 29.

For cooking and water heating the useful energy needs was calculated as the product of the FE intensity and the end-use technology mix as shown in Eq. C- 1.

$$UE\,{}^{j,k,app}_{p,i,s,y=0} = FEI^{j,k,\ app}_{p,i,s,y=0} \times Mix^{j,k,\ app}_{p,i,s,y=0} \qquad [ktoe]$$ **Eq. C- 1**

Where:

$UE^{j,k,app}_{p,i,s,y=0}$: The useful energy needs for the Residential sector population type *p*, energy carrier *i*, service *s*, and year y=0 [ktoe].

$FEI^{j,k,\ app}_{p,i,s,y}$: Presented in Eq. 4-34. The FE intensity per unit of appliance (e.g. appliance or technology) for population type y for FE carrier i attributable to FE service *s,* in year y for each sector *j*, and subsector *k* when applicable [ktoe/appliance]

$Mix^{j,k,\ app}_{p,i,s,y=0}$: Presented in Eq. 4-35. Representative efficiency of the end-use technology mix for the FE service *s* – carrier *i* combination in year *y*, calculated at for each sector *j*, and subsector *k* when applicable. [%]

Following the calculation for the useful energy needs for each technology and carrier combination an aggregate useful energy needs for the energy service was calculated for each population type. The aggregate useful energy needs for each population type was calculated with a weighted average of the useful energy needs of each technology and carrier combination as shown in Eq. C- 2 below.

The ownership levels for the Residential sector for the current alternative are presented below in Table C- 29.

The calculated useful energy needs for the energy services of interest in the current alternative for the population types are presented in Table C- 30.

$$UE\ aggregate^{Res}_{p,s,y=0} = \frac{\sum_i UE\,{}^{j,app}_{p,i,s,y=0} \times Access_{\ p,i} \times HHS_{p,y} \times Own_{p,i,s,y} \qquad [ktoe]}{\sum_i Access_{\ p,i} \times HHS_{p,y} \times Own_{p,i,s,y}}$$ **Eq. C- 2**

Where:

$UE\ aggregate^{Res}_{p,s,y=0}$: The aggregate useful energy needs for the Residential sector, population type *p*, energy service *s*, and year y=0 [ktoe].

$Access_{\ p,i}$: See Eq. 4-33

$HHS_{p,y}$: See Eq. 4-33

$Own_{p,i,s,y}$: See Eq. 4-33

The FE demand for each year is then calculated based on the sum of the FE demand previously attributed to the FE carrier i and the additional demand which arises from the shift in demand from the traditional carriers t, e.g. fuelwood, charcoal and kerosene as shown in Eq. C- 3.

$$Q_{p,s,i,y}^{Res,shift} = Access_{\ p,i} \times FEI_{p,i,s,y}^{Res,app} \times Own_{p,i,s,y} + share_i \sum_t Access_{\ p,t} \times \Delta Own_{p,t,s,y} \times \frac{UE\ aggregate_{p,s,y=0}^{Res}}{Mix_{p,t,s,y}^{j,k,\ app}} \quad \textbf{Eq. C- 3}$$

Where:

$Q_{p,s,i,y}^{Res,\ shift}$: The new FE demand reflecting the shift from traditional fuels to modern fuels for sector j, population type p, energy service s, FE carrier i, and year y [ktoe]

$share_i$: Share of the shift from traditional FE carrier t which is attributed to calculated carrier i, FE demand [%]

$\Delta Own_{p,t,s,y}$: Change in ownership levels of technologies for traditional FE carrier t from year *y-1* to year y [appliance/household]

The shares assumed for $share_i$ are presented below in Table C- 31. For cooking 100% of fuelwood and charcoal demand shifts to LPG cooking as only these three FE carriers are considered for cooking in the current work. For water heating 90% and 10% of charcoal and fuelwood demand is shifted to LPG and electricity appliances respectively. For lighting 100% of kerosene lighting demand shifts to electricity FE demand.

Table C- 29 - Residential: Household ownership of appliances by service & carrier: Alt. 9 UNIMOD

Household ownership [appliances/household] FE service – carrier combination	2008	2012	2015	2020
Cooking – Biomass				
CoreUrban	0.2031	0.1354	0.0846	0.0000
PeriUrban	0.8431	0.5621	0.3513	0.0000
Rural	0.8431	0.5621	0.3513	0.0000
Cooking – Charcoal				
CoreUrban	0.5774	0.3849	0.2406	0.0000
PeriUrban	0.1415	0.0944	0.0590	0.0000
Rural	0.1415	0.0944	0.0590	0.0000
Cooking – LPG				
CoreUrban	0.2195	0.2548	0.3017	0.4432
PeriUrban	0.0154	0.0179	0.0211	0.0311
Rural	0.0154	0.0179	0.0211	0.0311
Lighting – Kerosene				
CoreUrban	0.1910	0.1270	0.0800	0.0000
PeriUrban	0.5130	0.3420	0.2140	0.0000
Rural	0.8200	0.5470	0.3420	0.0000
Lighting – Electricity- Grid				
CoreUrban	0.8090	0.9391	1.1118	1.6330
PeriUrban	0.4870	0.5653	0.6693	0.9830
Rural	0.1800	0.2090	0.2474	0.3633
Water heating – Biomass				
CoreUrban	0.2031	0.1354	0.0846	0.0000
PeriUrban	0.8431	0.5621	0.3513	0.0000
Rural	0.8431	0.5621	0.3513	0.0000
Water heating – Charcoal				
CoreUrban	0.5774	0.3849	0.2406	0.0000
PeriUrban	0.1415	0.0944	0.0590	0.0000
Rural	0.1415	0.0944	0.0590	0.0000
Water heating – LPG				
CoreUrban	0.2195	0.2548	0.3017	0.4432
PeriUrban	0.0154	0.0179	0.0211	0.0311
Rural	0.0154	0.0179	0.0211	0.0311
Water heating – Electricity- Grid				
CoreUrban	0.0380	0.0441	0.0522	0.0767
PeriUrban	0.0108	0.0125	0.0148	0.0217
Rural	0.0108	0.0125	0.0148	0.0217

(EC, 2006a), calculations

Table C- 30 - Useful energy needs for cooking, water heating and lighting: Alt. 9 UNIMOD

Useful energy needs		CoreUrban	PeriUrban	Rural
Cooking	[ktoe/HHS/year] (kWh/HHS/year)	1.29E-04 (1,502.96)	1.48E-04 (1,725.60)	2.17E-04 (2,518.67)
Water heating	[ktoe/HHS/year] (kWh/HHS/year)	4.48E-05 (520.61)	5.04E-05 (585.99)	7.27E-05 (844.89)
Lighting	[lumens/lamp point]	1565.29	796.04	235.07

Calculations

Table C- 31 – Share of the shift of FE demand from traditional FE carrier attributable to modern FE carrier

Share of Traditional FE Carrier demand [%]		LPG	Electricity
Cooking	Fuelwood	100	-
	Charcoal	100	-
Water heating	Fuelwood	90	100
	Charcoal	90	100
Lighting	Kerosene	-	100

Assumptions

The electricity generation expansion plan is detailed in Table C- 32 for the planning horizon and presented in Figure C- 6.

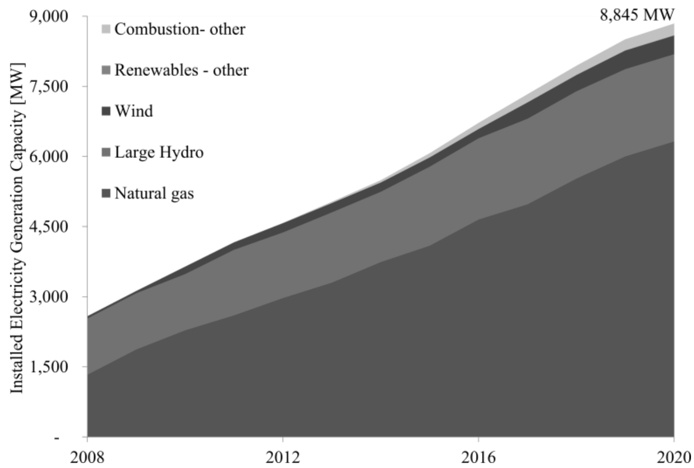


Figure C- 6 - Installed electricity generation capacity: Ghana Alt 9. Univ. Access & Mod. Services

Table C- 32 - Electricity generation expansion plan – Alt. 9 UNIMOD

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power								220	220	320	320	320	320	320
	CEN Power2								110	110	210	210	210	210	210
	Generic GT Plant 150MW + 100MW										150	250	250	250	250
CCGT	Tema		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2									210	360	360	360	360	360
	Generic Plant 60MW 1										60	60	60	60	60
	Generic Plant 450MW 1											225	450	450	450
	Generic Plant 450MW 2												225	450	450
	Generic Plant 450MW 3													250	450
	Generic Plant 450MW 4													60	120
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
Wind	Generic Wind Farm 1	0	50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind Farm 2	0	0	0	0	0	0	0	0	0	0	150	150	200	200
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
Mun. Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants										20	40	60	80	80
Wood wastes	Generic wood wastes		3	3	3	3	3	3	3	3	3	4	4	4	15
Total		1,984	2,587	3,128	3,649	4,170	4,581	5,032	5,494	6,071	6,720	7,333	7,942	8,568	8,845

Alt. 10 DIVPES

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5, in which the national grid is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is detailed in Table C- 33 for the planning horizon and presented in Figure C- 7.

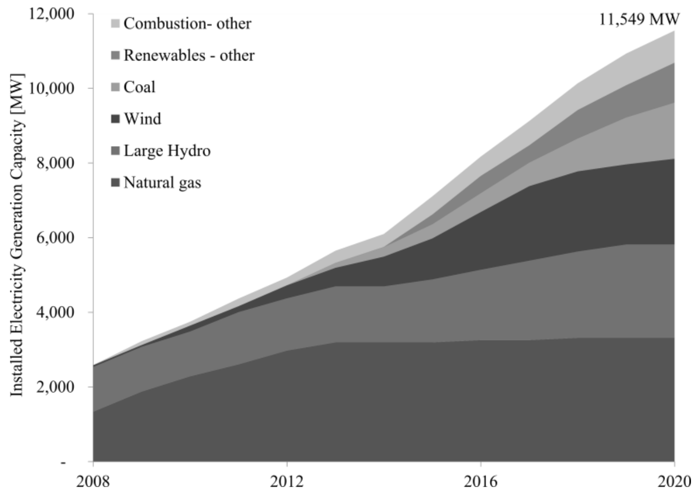


Figure C- 7 - Installed electricity generation capacity: Ghana Alt 10. Diverse PE supply

Table C- 33 - Electricity generation expansion plan – Alt. 10 DIVPES

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Coal	Generic Coal Plant 250MW 1							125	250	250	250	250	250	250	250
	Generic Coal Plant 250MW 2									125	250	250	250	250	250
	Generic Coal Plant 250MW 3											125	250	250	250
	Generic Coal Plant 250MW 4												125	250	250
	Generic Coal Plant 250MW 5													125	250
	Generic Coal Plant 250MW 6													125	250
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	320	320	320
	Effasu						150	150	150	150	150	150	150	150	150
CCGT	Tema		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Generic Plant 60MW + 60MW 1										60	60	120	120	120
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Daboya Hydro													43	43

	Generic Large Hydro 1										150	150	300	300	300
	Generic Large Hydro 2											150	150	295	295
Wind	Generic Wind Farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind Farm 2						150	150	300	300	300	300	300	300	300
	Generic Wind Farm 3							150	150	300	300	300	300	300	300
	Generic Wind Farm 4								150	150	300	300	300	300	300
	Generic Wind Farm 5									150	150	300	300	300	300
	Generic Wind Farm 6										150	150	300	300	300
	Generic Wind Farm 7											150	150	150	300
	Generic Offshore Wind farm 1										150	150	150	150	150
	Generic Offshore Wind farm 2											150	150	150	150
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Solar PV plant 3									2.5	5	5	5	5	5
	Generic Large Solar PV plant 1												200	200	200
	Generic Large Solar PV plant 2														200
Solar conc. thermal	Generic Concentrated Solar plant 1									50	50	50	50	50	50
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
	Generic additional Landfills												2	4	6
Mun. Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants										10	20	30	40	50
Wood wastes	Generic wood wastes 1			100	100	100	100	100	100	100	100	100	150	150	150
	Generic wood wastes 2					100	100	100	100	100	100	100	100	100	100
	Generic wood wastes 3							100	100	100	100	100	100	100	100
	Generic wood wastes 4									100	100	100	100	100	100
	Generic wood wastes 5											100	100	100	100
	Generic wood wastes 6													100	100
Marine wave	Generic Wave Power 1									200	200	200	200	200	200
	Generic Wave Power 2												100	100	100
Marine tidal	Generic Tidal Range Barrage Power 1										200	200	200	200	200
	Generic Tidal Range Barrage Power 2													100	100
Total		1,984	2,584	3,225	3,746	4,367	4,931	5,649	6,099	7,106	8,172	9,124	10,135	10,931	11,549

Alt. 11 LOWINV

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is shown in Table C- 34 for the planning horizon and presented in Figure C- 8.

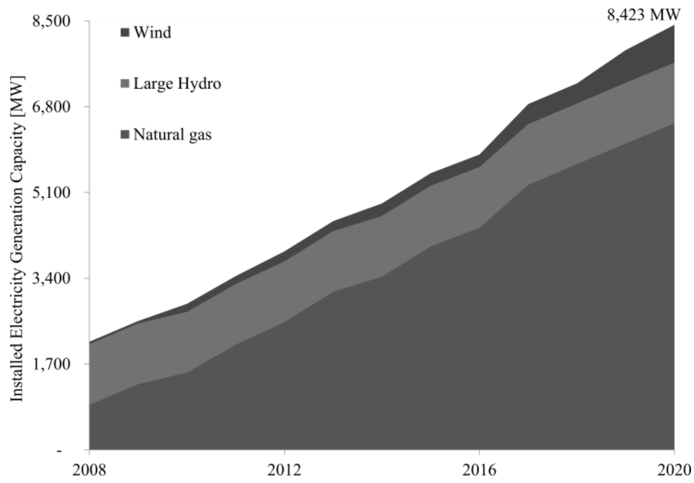


Figure C- 8 - Installed electricity generation capacity: Ghana Alt 11. Lowest investment cost

Table C- 34 - Electricity generation expansion plan – Alt. 11 LOWINV

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	320	320	320
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power										220	320	320	320	320
	CEN Power2												110	220	220
	Generic Plant 150MW + 150MW 1			150	150	300	300	300	300	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 2				150	150	300	300	300	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 3					150	150	300	300	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 4					150	150	300	300	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 5						150	150	300	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 6							150	150	300	300	300	300	300	300
	Generic Plant 150MW + 150MW 7							150	150	300	150	300	300	300	300
	Generic Plant 150MW + 150MW 8								150	150	300	300	300	300	300
	Generic Plant 150MW + 150MW 9									150	150	300	300	300	300
	Generic Plant 150MW + 150MW 10									150	150	300	300	300	300
	Generic Plant 150MW + 150MW 11										150	150	300	300	300
	Generic Plant 150MW + 150MW 12											150	150	300	300
	Generic Plant 150MW + 150MW 13											150	150	300	300
	Generic Plant 150MW + 150MW 14												150	150	300
	Generic Plant 150MW + 150MW 15													150	150
	Generic Plant 100MW 1														100
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
Wind	Generic Wind Farm 1		50	50	160	160	200	200	250	250	250	250	250	250	250
	Generic Wind Farm 2											150	150	300	300
	Generic Wind Farm 3													100	200
Total		1,983	2,143	2,553	2,893	3,443	3,933	4,533	4,883	5,483	5,853	6,853	7,263	8,073	8,423

Alt. 12 LOWRUN

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is detailed in Table C- 35 for the planning horizon and presented in Figure C- 9.

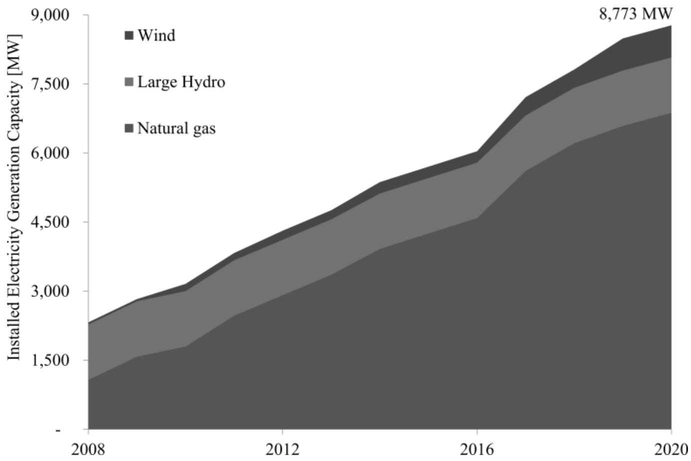


Figure C- 9 - Installed electricity generation capacity: Ghana Alt 12. Lowest running cost

Table C- 35 - Electricity generation expansion plan – Alt. 12 LOWRUN

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
CCGT	Tema		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di			110	220	330	440	550	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2									110	220	360	360	360	360
	Kpone turbine											210	360	360	360
	Generic Plant 450MW 1			225	225	450	450	450	450	450	450	450	450	450	450
	Generic Plant 450MW 2					225	225	450	450	450	450	450	450	450	450
	Generic Plant 450MW 3						225	225	450	450	450	450	450	450	450
	Generic Plant 450MW 4								225	225	225	450	450	450	450
	Generic Plant 450MW 5									225	225	450	450	450	450
	Generic Plant 450MW 6										225	225	450	450	450
	Generic Plant 450MW 7											225	225	450	450
	Generic Plant 450MW 8												225	225	450
	Generic Plant 450MW 9													150	210
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
Wind	Generic Wind Farm 1		50	50	160	160	200	200	250	250	250	250	250	250	250
	Generic Wind Farm 2											150	150	300	300
	Generic Wind Farm 3													150	150
Total		1,983	2,323	2,828	3,158	3,828	4,313	4,758	5,368	5,703	6,038	7,213	7,813	8,488	8,773

Alt. 13 LOCREC

The electricity access assumptions are identical to those of the MNIGRD alternative as presented previously in Table C- 5 for new connections. The shares of households connected follow the assumptions detailed previously for the MNIGRD alternative in Section 5.10.3 in which the MNIGRD option is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is detailed in Table C- 36 for the planning horizon and presented in Figure C- 10.

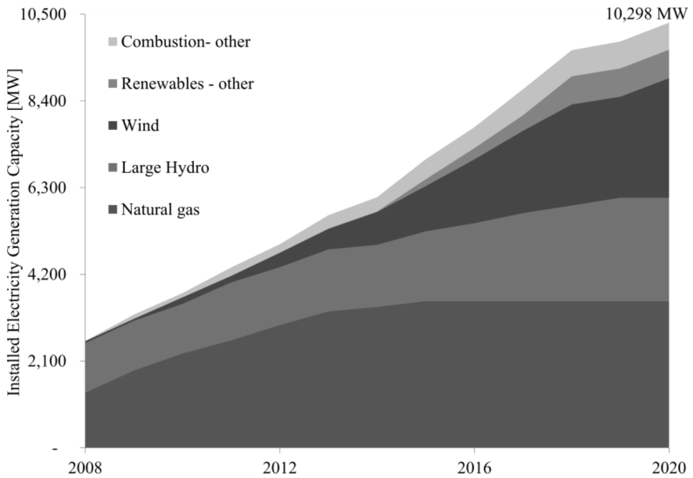


Figure C- 10 - Installed electricity generation capacity: Ghana Alt 13. Local energy resources

Table C- 36 - Electricity generation expansion plan – Alt. 13 LOCREC

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco + Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	320	320	320
	Effasu						150	150	150	150	150	150	150	150	150
CCGT	Tema		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36

	Daboya Hydro													43	43
	Generic Large Hydro 1										150	150	300	300	300
	Generic Large Hydro 2											150	150	295	295
Wind	Generic Wind Farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind Farm 2						150	150	300	300	300	300	300	300	300
	Generic Wind Farm 3							150	150	300	300	300	300	300	300
	Generic Wind Farm 4								150	150	300	300	300	300	300
	Generic Wind Farm 5									150	150	300	300	300	300
	Generic Wind Farm 6										150	150	300	300	300
	Generic Wind Farm 7											150	150	150	300
	Generic Wind Farm 8												150	150	300
	Generic Wind Farm 9												150	150	300
	Generic Offshore Wind farm 1										150	150	150	150	150
	Generic Offshore Wind farm 2											150	150	150	150
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Solar PV plant 3									2.5	5	5	5	5	5
	Generic Solar PV plant 4										2.5	5	5	5	5
	Generic Solar PV plant 5											2.5	5	5	5
	Generic Solar PV plant 6												2.5	5	5
	Generic Large Solar PV plant 2												200	200	200
Solar conc. thermal	Generic Concentrated Solar plant 1									50	50	50	50	50	50
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
Mun. Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
Wood wastes	Generic wood wastes 1			100	100	100	100	100	100	100	100	100	100	100	100
	Generic wood wastes 2					100	100	100	100	100	100	100	100	100	100
	Generic wood wastes 3							100	100	100	100	100	100	100	100
	Generic wood wastes 4									100	100	100	100	100	100
	Generic wood wastes 5											100	100	100	100
Marine wave	Generic Wave Power 1									100	100	100	100	100	100
	Generic Wave Power 2												100	100	100
Marine tidal	Generic Tidal Range Barrage Power 1										100	100	100	100	100
	Generic Tidal Range Barrage Power 2												100	100	100
Total		1,984	2,584	3,225	3,746	4,367	4,931	5,634	6,069	6,991	7,765	8,587	9,631	9,842	10,298

Alt. 14 HGMAIN

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is detailed in Table C- 37 for the planning horizon and presented in Figure C- 11.

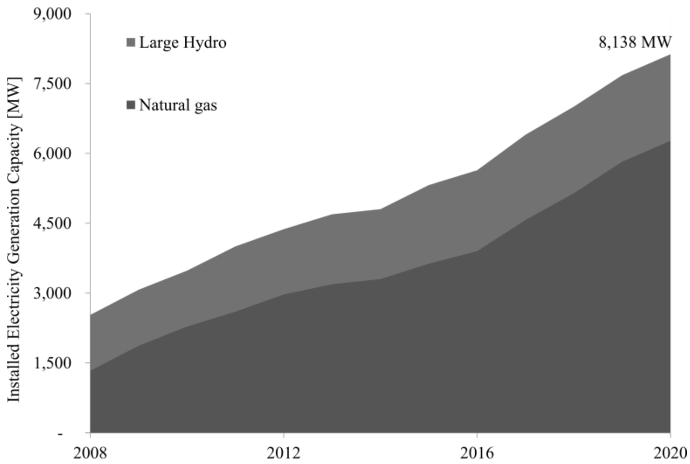


Figure C- 11 - Installed electricity generation capacity: Ghana Alt 14. Highly maintainable

Table C- 37 - Electricity generation expansion plan – Alt. 14 HGMAIN

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	420	420	420
	Effasu						150	150	150	150	150	150	150	150	150
	CEN Power									220	320	320	320	320	320
	CEN Power2										110	220	220	220	220
	Generic GT Plant 150MW + 100MW 1											150	250	250	250
CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
	Sunon Asogli Power Plant 2							110	220	360	360	360	360	360	360
	Kpone turbine 2											210	360	360	360
	Generic Plant 60MW + 60MW 1										60	120	120	120	120
	Generic Plant 450MW 1												225	450	450
	Generic Plant 450MW 2													225	450
	Generic Plant 450MW 3													225	450
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Generic Large Hydro 1												28	28	28
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Total		1,984	2,534	3,075	3,486	4,006	4,376	4,806	4,916	5,463	5,781	6,405	7,008	7,684	8,138

Alt. 15 EXPREN

The electricity access assumptions are identical to those of the Reference Projection as presented previously in Table C- 1 for new connections. The shares of households connected follow the assumptions detailed previously in Section 5.5 in which the national grid is favored for new connections.

The DSM considerations for the current alternative are identical to those described previously in Alt. 6 DIVRSI.

The electricity generation expansion plan is detailed in Table C- 38 for the planning horizon and shown in Figure C-12.

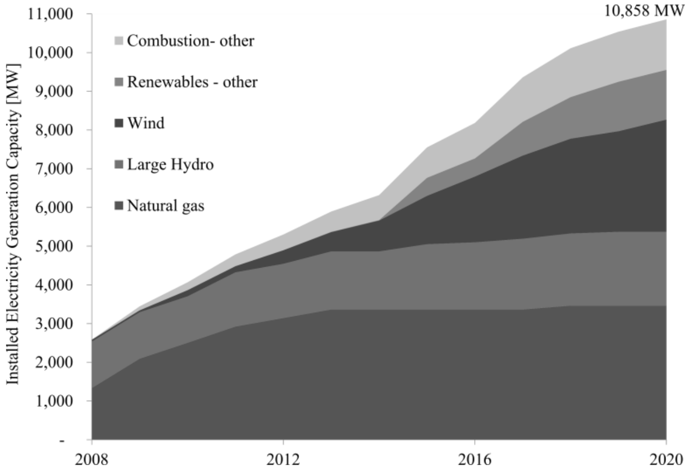


Figure C- 12 - Installed electricity generation capacity: Ghana Alt 15. Expanded renewables

Table C- 38 - Electricity generation expansion plan – Alt. 15 EXPREN

Installed Capacity [MW]	Electricity Generation Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GT	Tapco +Tico gas	660	660	660	660	660	660	660	660	660	660	660	660	660	660
	Osagyefo Power Barge	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Distributed Gas Turbines		150	150	150	150	150	150	150	150	150	150	150	150	150
	Mines Reserve Plant				80	80	80	80	80	80	80	80	80	80	80
	CENIT turbine		110	150	150	150	150	150	150	150	150	150	150	150	150
	Kpone turbine 1			220	220	320	320	320	320	320	320	320	320	320	320
	Effasu			220	220	320	320	320	320	320	320	320	420	420	420
CCGT	Tema CCGT		110	220	330	440	550	660	660	660	660	660	660	660	660
	Ta'di CCGT			110	330	440	550	660	660	660	660	660	660	660	660
	Sunon Asogli Power Plant 1		180	240	240	240	240	240	240	240	240	240	240	240	240
Hydro	Akos & Kpg Hydro	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198	1,198
	Bui Hydro					200	200	300	300	400	400	400	400	400	400
	Juale Hydro									87	87	87	87	87	87
	Pwalugu Hydro										48	48	48	48	48
	Hermang Hydro											93	93	93	93
	Kulpawn Hydro												36	36	36
	Daboya Hydro													43	43
Wind	Generic Wind farm 1		50	50	160	160	200	200	200	200	200	200	200	200	200
	Generic Wind farm 2						150	150	300	300	300	300	300	300	300
	Generic Wind farm 3							150	150	300	300	300	300	300	300
	Generic Wind farm 4								150	150	300	300	300	300	300
	Generic Wind farm 5									150	150	300	300	300	300
	Generic Wind farm 6										150	150	300	300	300
	Generic Wind farm 7											150	150	150	300
	Generic Offshore Wind farm 1									150	300	300	300	300	300
	Generic Offshore Wind farm 2											150	300	300	300
	Generic Offshore Wind farm 3													150	300
Solar PV	Generic Solar PV plant 1						2.5	5	5	5	5	5	5	5	5
	Generic Solar PV plant 2								2.5	5	5	5	5	5	5
	Generic Solar PV plant 3									2.5	5	5	5	5	5
	Generic Solar PV plant 4											2.5	5	5	5

	Generic Solar PV plant 5													2.5	5
	Generic Large Solar PV plant 1									200	200	200	200	200	200
	Generic Large Solar PV plant 2											200	200	200	200
	Generic Large Solar PV plant 3												200	200	200
	Generic Large Solar PV plant 4													200	200
Solar conc. thermal	Generic Concentrated Solar plant 1									50	50	50	50	50	50
Small Hydro	Generic Small Hydro	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Small Wind	Generic Small Wind	0.5	0.5	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2.5	4.5
Landfill gas	Landfill(Accra)					1	1	1	1	1	1	1	2	2	2
	Landfill(Kumasi)						1	1	1	1	1	1	2	2	2
	Landfill(Ta'di)							1	1	1	1	1	2	2	2
	Landfill(Tamale)								1	1	1	1	1	1	1
	Landfill(Cape Coast)								1	1	1	1	1	1	1
	Landfill(Winneba, Obuasi)										1	1	1	1	1
	Landfill(K'dua Ho, Sunyani)											3	3	3	3
	Landfills (Bolga, Wa Nkawkaw, Techiman, Ash-Manpong)														2
Mun. Solid Waste	Municipal Solid Waste (Accra-Tema)							20	20	40	40	40	40	40	40
	Municipal Solid Waste (Kumasi)								20	20	20	40	40	40	40
	Municipal Solid Waste (Secondi-Ta'di)									20	20	20	20	20	20
	Municipal Solid Waste (Tamale)										20	20	20	20	20
	Municipal Solid Wastes (Cape Coast)													20	20
	Generic Municipal Solid Waste Plants										10	20	30	40	50
Wood waste	Generic wood wastes 100MW+100MW 1			100	100	100	100	100	100	100	100	200	200	200	200
	Generic wood wastes 100MW+ 100MW 2				100	100	100	100	100	100	100	100	200	200	200
	Generic wood wastes 100MW+ 100MW 3					100	100	100	100	100	100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 4						100	100	100	100	100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 5							100	100	100	100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 6								100	100	100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 7									100	100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 8										100	100	100	100	100
	Generic wood wastes 100MW+ 100MW 9											100	100	100	100
Marine wave	Generic Wave Power 1									200	200	200	200	200	200
Marine tidal	Generic Tidal Range Barrage Power 1											200	200	200	200
Total		1,984	2,584	3,445	4,066	4,787	5,301	5,894	6,319	7,551	8,182	9,362	10,113	10,540	10,858

Appendix D

Evaluation of alternatives

D.1 - Partial value functions for decision conference- Preliminary set of EP alternatives

The partial value functions for the preliminary set of EP alternatives constructed for the DC held as part of the case study were discussed in assessing the performance and value scoring of alternatives in Section 6.3.1. The Partial value function for attribute 1, PE security, was presented in Figure 6-1 in Section 6.3.1. The partial value functions for the remaining attributes are presented for the remaining attributes in Figure D- 1, Figure D- 2, Figure D- 3, Figure D- 4, Figure D- 5, and Figure D- 6.

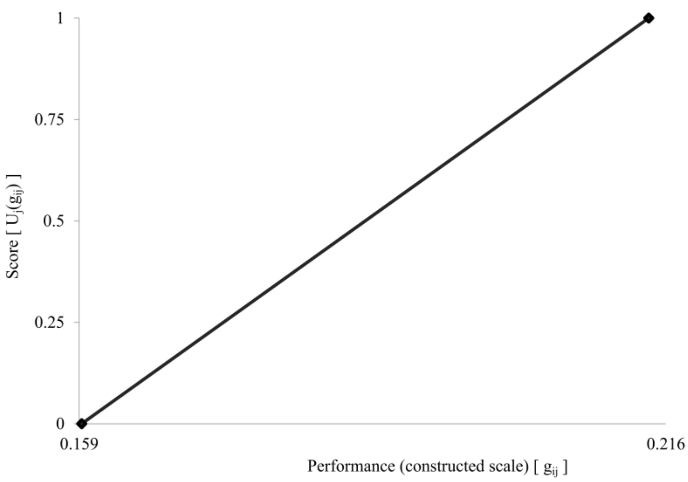


Figure D- 1 – Partial value function - Attribute 2 Adequacy of electricity generation: Case study

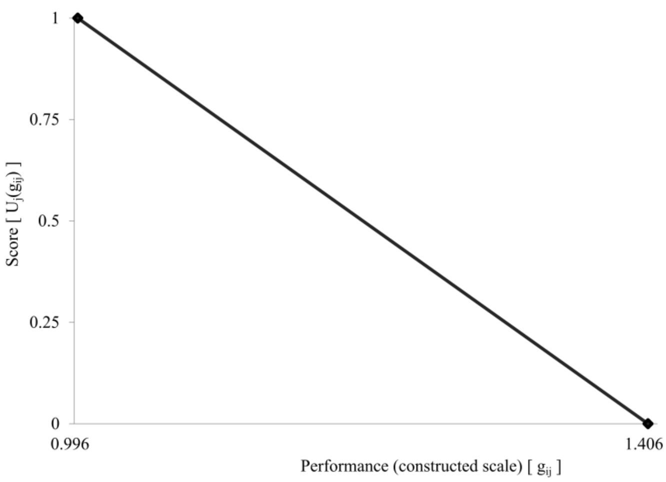
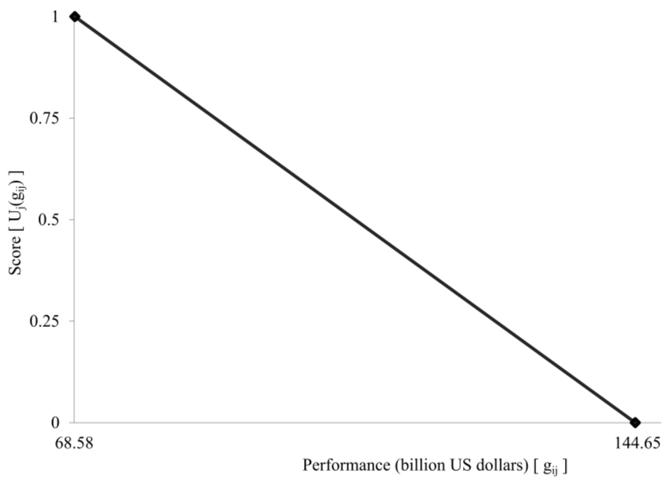


Figure D- 2 – Partial value function - Attribute 3 Maintainability of electricity generation: Case study



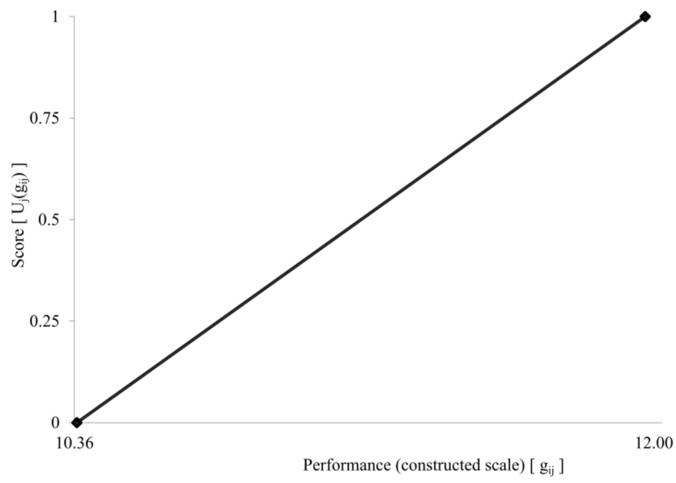
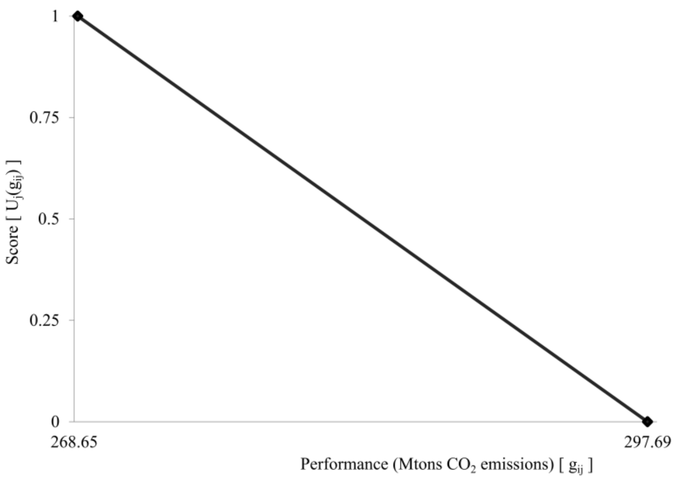


Figure D- 3 – Partial value function - Attribute 4 Cost (Inv., Main., & Oper.): Case study

Figure D- 4 – Partial value function - Attribute 5 Access to modern energy services: Case study



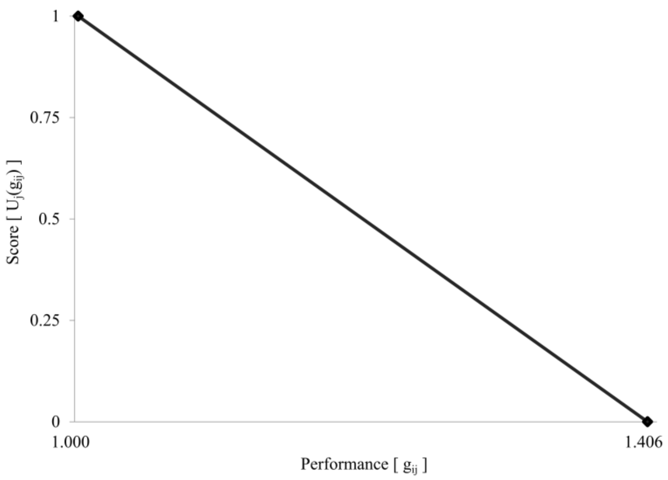


Figure D- 5 – Partial value function - Attribute 6 Impact on global climate: Case study

Figure D- 6 – Partial value function - Attribute 7 Impact on local environment: Case study

D.2 -Partial value functions for expanded EP 2008-2020 alternative set

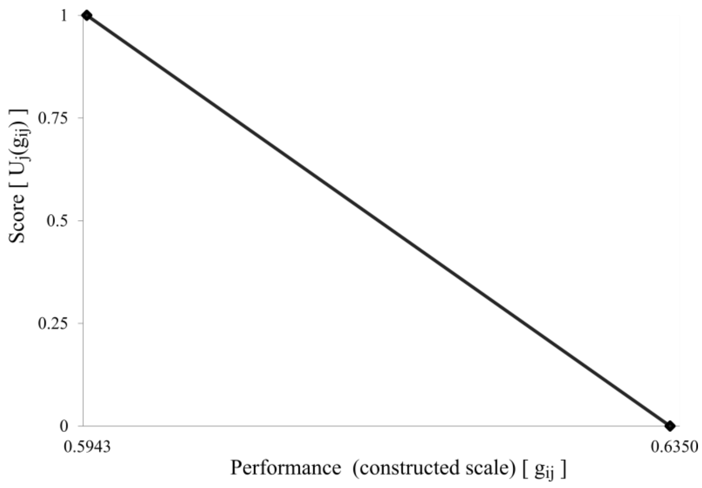


Figure D- 7 – Partial value function – Expanded alternative set - Attribute 1 PE Security: Case study

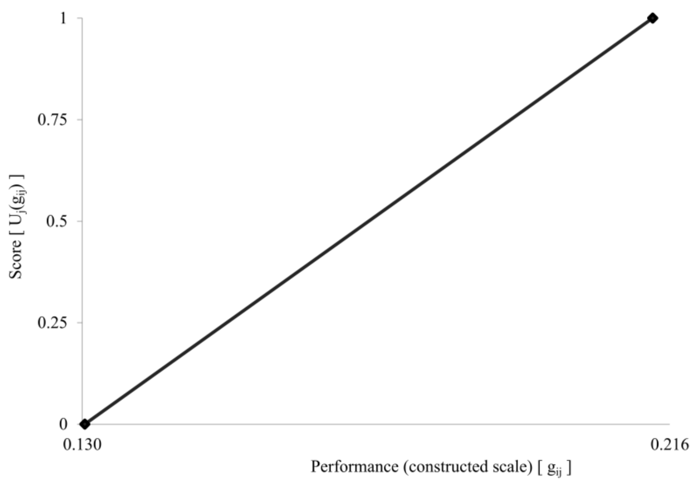


Figure D- 8 – Partial value function – Expanded alternative set - Attribute 2 Adequacy of electricity generation: Case study

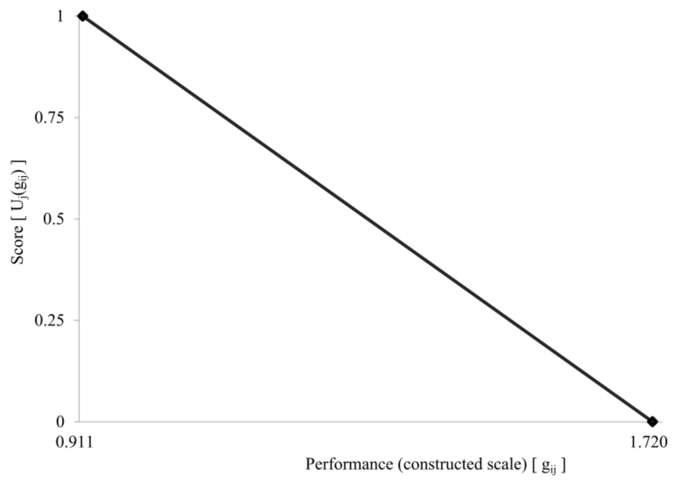


Figure D- 9 – Partial value function – Expanded alternative set - Attribute 3 Maintainability of electricity generation: Case study

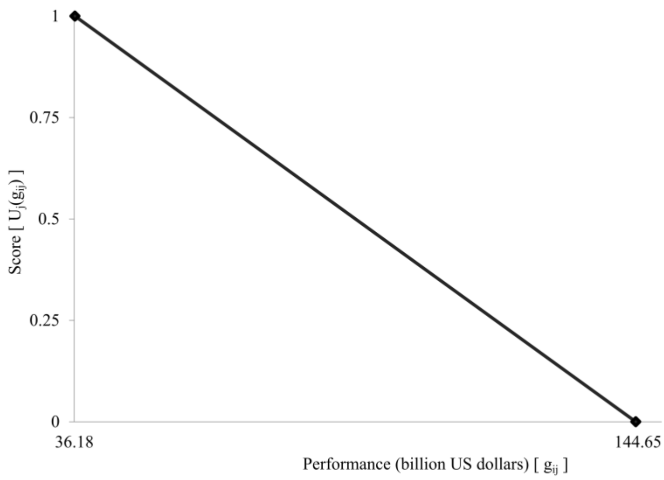


Figure D- 10 – Partial value function – Expanded alternative set - Attribute 4 Cost (Inv., Main., & Oper.): Case study

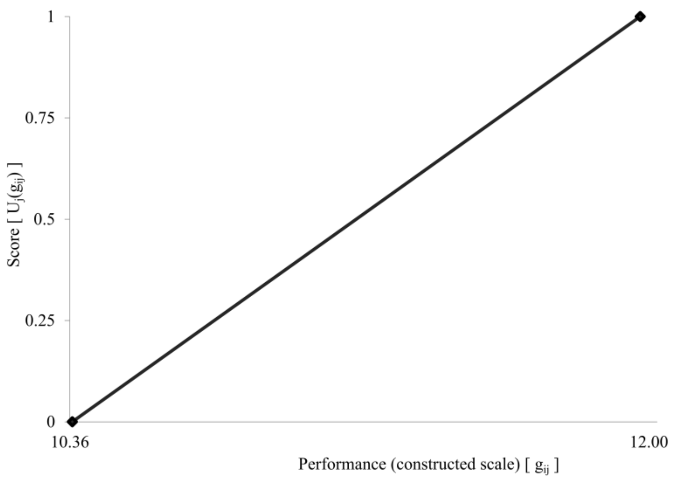


Figure D- 11 – Partial value function – Expanded alternative set - Attribute 5 Access to modern energy services: Case study

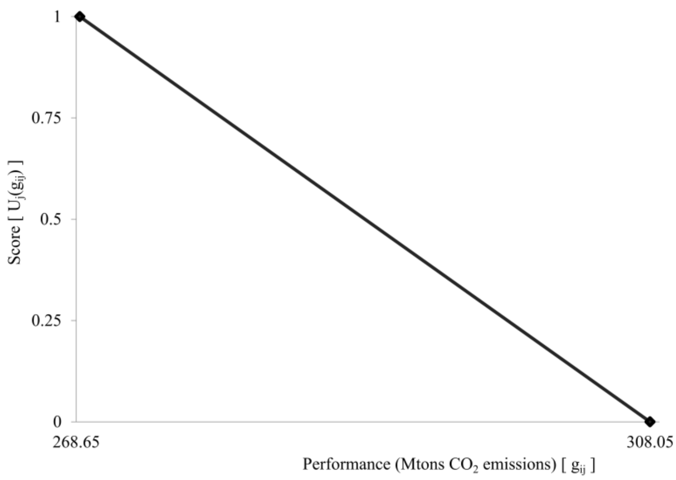


Figure D- 12 – Partial value function – Expanded alternative set - Attribute 6 Impact on global climate: Case study

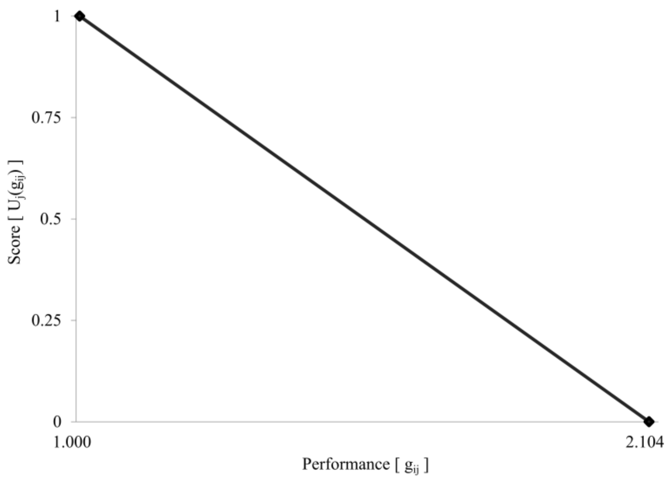


Figure D- 13 – Partial value function – Expanded alternative set - Attribute 7 Impact on local environment: Case study

D.3 -Evaluation of alternatives without preference information

The rank acceptability indexes corresponding to Figure 6-3 are shown in Table D- 1.

Table D- 1 - Rank acceptabilities – No preference information – DC: Case study

Alternative	Holistic Acceptability Index[1]	Rank Acceptability Index							
		R1[2]	R2	R3	R4	R5	R6	R7	R8
DIVRSII	0.709	0.494	0.318	0.118	0.054	0.016	0.000	0.000	0.000
DIVRSIII	0.403	0.205	0.067	0.201	0.174	0.077	0.084	0.054	0.139
DIVRSI	0.390	0.000	0.468	0.325	0.131	0.060	0.016	0.000	0.000
DSMREF	0.349	0.103	0.071	0.227	0.324	0.226	0.049	0.000	0.000
YNGREN	0.315	0.153	0.023	0.079	0.142	0.117	0.071	0.091	0.326
STDALN	0.239	0.046	0.051	0.016	0.149	0.284	0.169	0.260	0.025
PRVREN	0.159	0.000	0.000	0.000	0.016	0.105	0.376	0.442	0.061
MNIGRD	0.155	0.000	0.001	0.035	0.009	0.116	0.234	0.153	0.451

1. Centroid meta-weights (Section 3.9.2.5)
2. Rank

D.4 -Evaluation of alternatives with preference information

D.4.1 -SMAA-2 analysis

The rank acceptability indexes corresponding to Figure 6-5 are shown in Table D- 2.

Table D- 2 - Rank acceptabilities – ECOWAS+ objective set – DC: case study

Alternative	Holistic Acceptability Index[1]	Rank Acceptability Index							
		R1[2]	R2	R3	R4	R5	R6	R7	R8
DIVRSII	0.992	0.985	0.012	0.003	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.497	0.000	0.984	0.013	0.003	0.000	0.000	0.000	0.000
YNGREN	0.283	0.015	0.001	0.469	0.243	0.207	0.019	0.014	0.032
DSMREF	0.256	0.000	0.000	0.341	0.257	0.341	0.061	0.000	0.000
DIVRSIII	0.245	0.001	0.003	0.174	0.485	0.237	0.096	0.003	0.002
PRVREN	0.168	0.000	0.000	0.000	0.010	0.151	0.703	0.089	0.048
STDALN	0.139	0.000	0.000	0.000	0.003	0.063	0.070	0.338	0.526
MNIGRD	0.137	0.000	0.000	0.000	0.000	0.001	0.051	0.557	0.392

1. Centroid meta-weights (Section 3.9.2.5)
2. Rank

The rank acceptability indexes corresponding to Figure 6-7 are shown in Table D- 3.

Table D- 3 - Rank acceptabilities – ECOWAS objective set – DC: case study

Alternative	Holistic Acceptability Index[1]	Rank Acceptability Index R1[2]	R2	R3	R4	R5	R6	R7	R8
DIVRSII	0.965	0.931	0.065	0.004	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.488	0.000	0.929	0.067	0.004	0.000	0.000	0.000	0.000
YNGREN	0.372	0.069	0.002	0.851	0.059	0.019	0.000	0.000	0.000
DIVRSIII	0.226	0.000	0.004	0.014	0.555	0.286	0.140	0.001	0.000
DSMREF	0.221	0.000	0.000	0.064	0.352	0.435	0.149	0.000	0.000
PRVREN	0.178	0.000	0.000	0.000	0.029	0.260	0.710	0.001	0.000
MNIGRD	0.139	0.000	0.000	0.000	0.000	0.000	0.001	0.762	0.237
STDALN	0.129	0.000	0.000	0.000	0.000	0.000	0.000	0.237	0.763

1. Centroid meta-weights (Section 3.9.2.5)
2. Rank

The rank acceptability indexes corresponding to Figure 6-8 are shown in Table D- 4.

Table D- 4 - Rank acceptabilities – Dev-C objective set – DC: case study

Alternative	Holistic Acceptability Index[1]	Rank Acceptability Index R1[2]	R2	R3	R4	R5	R6	R7	R8
DIVRSII	0.753	0.513	0.468	0.020	0.000	0.000	0.000	0.000	0.000
DIVRSIII	0.663	0.487	0.026	0.487	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.413	0.000	0.487	0.493	0.020	0.000	0.000	0.000	0.000
YNGREN	0.244	0.000	0.020	0.000	0.766	0.211	0.001	0.001	0.002
DSMREF	0.209	0.000	0.000	0.000	0.214	0.725	0.061	0.000	0.000
PRVREN	0.168	0.000	0.000	0.000	0.000	0.061	0.929	0.006	0.004
MNIGRD	0.136	0.000	0.000	0.000	0.000	0.002	0.004	0.627	0.367
STDALN	0.132	0.000	0.000	0.000	0.000	0.001	0.005	0.367	0.627

1. Centroid meta-weights (Section 3.9.2.5)
2. Rank

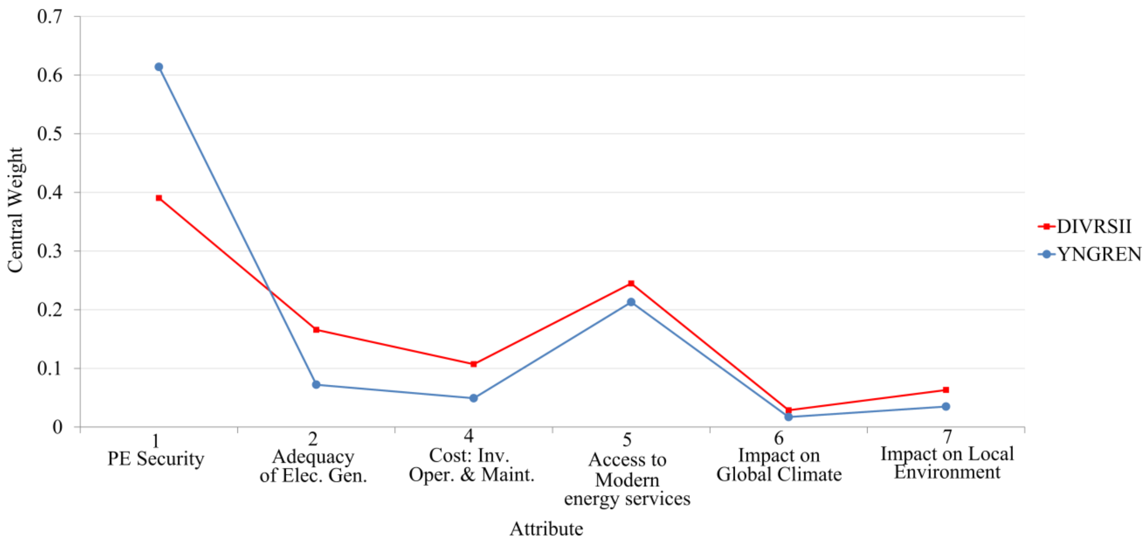


Figure D- 14 - Central weight vectors - ECOWAS objective set – DC: Case study

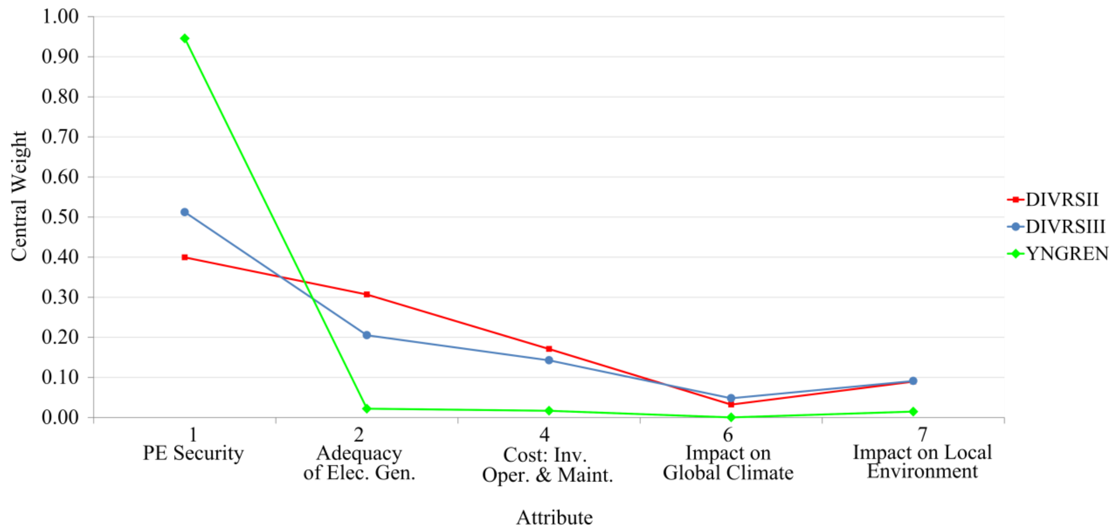


Figure D- 15 - Central weight vectors - Dev-C objective set - DC: Case study

D.5 - VIP analysis

D.5.1 - VIP Analysis

The values corresponding to Figure 6-9 are presented in Table D- 5. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 5 - Range of values and maximum regret - ECOWAS+ objective set - DC: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
DIVRSII	0.706	0.940	0.180	
DIVRSI	0.699	0.940	0.179	
DIVRSIII	0.483	0.966	0.517	
PRVREN	0.458	0.729	0.542	YES
YNGREN	0.400	1.000	0.409	
DSMREF	0.300	0.740	0.700	YES
MNIGRD	0.061	0.637	0.939	YES (Abs)
STDALN	0.000	0.658	1.000	YES (Abs)

The values corresponding to Figure 6-11 are presented in Table D- 6. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 6 - Range of values and maximum regret – ECOWAS objective set – DC: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
DIVRSI	0.507	0.940	0.493	
DIVRSII	0.507	0.940	0.493	
DIVRSIII	0.483	0.966	0.517	
PRVREN	0.458	0.729	0.542	
DSMREF	0.300	0.816	0.700	
MNIGRD	0.061	0.886	0.939	
YNGREN	0.000	1.000	1.000	
STDALN	0.000	1.000	1.000	

The values corresponding to Figure 6-12 are presented in Table D- 7. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 7 - Range of values and maximum regret – Dev-C objective set – DC: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
DIVRSI	0.507	1.000	0.493	
DIVRSII	0.507	1.000	0.493	
PRVREN	0.301	1.000	0.610	
DSMREF	0.300	1.000	0.700	
MNIGRD	0.061	1.000	0.939	
YNGREN	0.000	1.000	1.000	
STDALN	0.000	1.000	1.000	
DIVRSIII	0.000	0.966	1.000	

D.6 -Expanded alternatives evaluation

D.6.1 -SMAA-2 Analysis: Expanded alternatives

The values corresponding to Figure 6-13 are presented in Table D- 8.

Table D- 8 - Rank acceptabilities - No preference info. -Expanded alternatives (Exp. alt.): Case study

Alt.	Holistic Acc. Index[1]	Rank Acceptability Index														
		R1[2]	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
DIVRSII	0.453	0.195	0.212	0.227	0.171	0.076	0.060	0.034	0.022	0.003	0.000	0.000	0.000	0.000	0.000	0.000
HGMAIN*	0.404	0.198	0.132	0.148	0.107	0.088	0.119	0.123	0.030	0.024	0.015	0.008	0.007	0.003	0.000	0.000
UNIMOD*	0.392	0.180	0.121	0.132	0.166	0.136	0.116	0.073	0.049	0.020	0.004	0.002	0.001	0.000	0.000	0.000
YNGREN	0.324	0.209	0.035	0.040	0.033	0.057	0.061	0.058	0.069	0.066	0.054	0.057	0.087	0.126	0.039	0.010
DIVRSI	0.277	0.000	0.174	0.197	0.219	0.182	0.093	0.069	0.038	0.024	0.004	0.000	0.000	0.000	0.000	0.000
LOWRUN*	0.276	0.100	0.098	0.070	0.082	0.088	0.088	0.092	0.086	0.068	0.055	0.054	0.044	0.041	0.027	0.008
DIVRSIII	0.214	0.054	0.066	0.076	0.063	0.087	0.089	0.062	0.067	0.059	0.056	0.045	0.040	0.057	0.046	0.133
LOCREC*	0.213	0.031	0.122	0.047	0.066	0.085	0.078	0.076	0.082	0.077	0.072	0.083	0.113	0.067	0.001	0.000
LOWINV*	0.155	0.034	0.035	0.033	0.033	0.032	0.039	0.059	0.074	0.074	0.068	0.060	0.094	0.129	0.098	0.139
DSMREF	0.152	0.000	0.000	0.011	0.049	0.148	0.180	0.216	0.216	0.118	0.044	0.017	0.002	0.000	0.000	0.000
STDALN	0.113	0.000	0.003	0.013	0.009	0.012	0.045	0.061	0.148	0.178	0.181	0.179	0.105	0.053	0.013	0.000
PRVREN	0.101	0.000	0.000	0.000	0.000	0.001	0.011	0.034	0.082	0.160	0.255	0.282	0.147	0.027	0.001	0.000
MNIGRD	0.089	0.000	0.000	0.000	0.000	0.004	0.004	0.020	0.023	0.106	0.135	0.142	0.193	0.194	0.140	0.039
EXPREN*	0.083	0.000	0.002	0.009	0.002	0.005	0.017	0.023	0.013	0.022	0.052	0.050	0.074	0.127	0.219	0.386
DIVPES*	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.022	0.093	0.177	0.417	0.285

1. Holistic Acceptability Index - Centroid meta-weights (Section 3.9.2.5)
2. Rank
* “New” alternative – Expanded alternatives

The values corresponding to Figure 6-15 are presented in Table D- 9.

Table D- 9 - Rank acceptabilities - ECOWAS+ objective set - Exp. alt.: Case study

Alt.	Holistic Acc. Index[1]	Rank Acceptability Index														
		R1[2]	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
UNIMOD*	0.988	0.983	0.004	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSII	0.477	0.017	0.853	0.112	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOCREC*	0.301	0.001	0.129	0.003	0.497	0.236	0.118	0.014	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.262	0.000	0.013	0.854	0.114	0.019	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HGMAIN*	0.233	0.000	0.001	0.000	0.370	0.212	0.326	0.075	0.006	0.011	0.000	0.000	0.000	0.000	0.000	0.000
YNGREN	0.171	0.000	0.000	0.019	0.001	0.401	0.235	0.272	0.030	0.007	0.009	0.011	0.013	0.002	0.000	0.000
DSMREF	0.152	0.000	0.000	0.000	0.000	0.132	0.215	0.488	0.116	0.029	0.021	0.000	0.000	0.000	0.000	0.000
PRVREN	0.118	0.000	0.000	0.000	0.000	0.000	0.002	0.023	0.577	0.287	0.032	0.057	0.022	0.000	0.000	0.000
DIVRSIII	0.103	0.000	0.000	0.000	0.000	0.000	0.085	0.059	0.136	0.157	0.049	0.053	0.129	0.237	0.079	0.016
STDALN	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.036	0.200	0.324	0.225	0.212	0.000	0.000	0.000
MNIGRD	0.096	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.143	0.325	0.418	0.091	0.021	0.000	0.000
LOWINV*	0.091	0.000	0.000	0.000	0.000	0.000	0.014	0.055	0.067	0.050	0.039	0.148	0.221	0.348	0.058	0.000
EXPREN*	0.085	0.000	0.000	0.000	0.000	0.000	0.005	0.010	0.006	0.098	0.170	0.056	0.127	0.108	0.420	0.001
LOWRUN*	0.078	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.023	0.018	0.029	0.033	0.182	0.239	0.360	0.114
DIVPES*	0.068	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.045	0.084	0.869

1. Holistic Acceptability Index - Centroid meta-weights (Section 3.9.2.5)
2. Rank
* “New” alternative – Expanded alternatives

The values corresponding to Figure 6-17 are presented in Table D- 10.

Table D- 10 - Rank acceptabilities - ECOWAS objective set - Exp. alt.: Case study

Alt.	Holistic Acc. Index[1]	Rank Acceptability Index R1[2]	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
UNIMOD*	0.884	0.817	0.033	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSII	0.524	0.164	0.528	0.225	0.082	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOCREC*	0.335	0.019	0.289	0.007	0.645	0.039	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.328	0.000	0.150	0.536	0.229	0.085	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
YNGREN	0.204	0.000	0.000	0.083	0.007	0.741	0.105	0.055	0.008	0.001	0.000	0.000	0.001	0.000	0.000	0.000
HGMAIN*	0.168	0.000	0.000	0.000	0.036	0.132	0.647	0.099	0.041	0.045	0.000	0.000	0.000	0.000	0.000	0.000
DSMREF	0.137	0.000	0.000	0.000	0.000	0.002	0.062	0.673	0.111	0.066	0.087	0.000	0.000	0.000	0.000	0.000
PRVREN	0.121	0.000	0.000	0.000	0.000	0.000	0.000	0.041	0.645	0.279	0.033	0.002	0.001	0.000	0.000	0.000
DIVRSIII	0.105	0.000	0.000	0.000	0.001	0.000	0.139	0.050	0.091	0.128	0.166	0.035	0.096	0.106	0.149	0.039
EXPREN*	0.105	0.000	0.000	0.000	0.000	0.000	0.045	0.074	0.035	0.309	0.286	0.039	0.053	0.079	0.080	0.000
MNIGRD	0.091	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.041	0.232	0.453	0.158	0.069	0.047	0.000
STDALN	0.088	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.091	0.380	0.479	0.039	0.001	0.000
LOWINV*	0.085	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.054	0.089	0.056	0.059	0.134	0.409	0.183	0.007
LOWRUN*	0.076	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.031	0.049	0.032	0.067	0.163	0.387	0.255
DIVPES*	0.069	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.135	0.153	0.699

1. Holistic Acceptability Index - Centroid meta-weights (Section 3.9.2.5)
2. Rank
* "New" alternative – Expanded alternatives

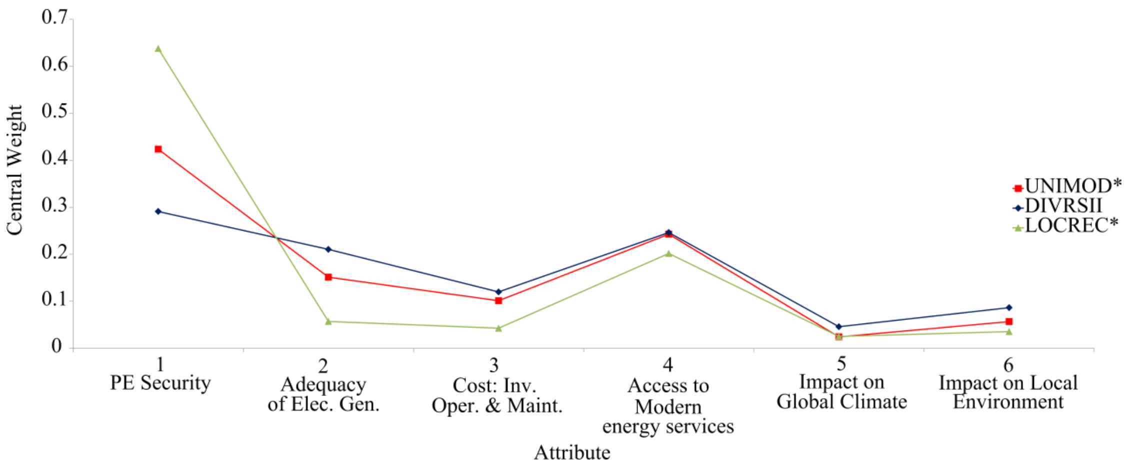


Figure D- 16 - Central weight vectors - ECOWAS objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

The values corresponding to Figure 6-18 are presented in Table D- 11.

Table D- 11 - Rank acceptabilities – Dev-C objective set - Exp. alt.: Case study

Alt.	Holistic Acc. Index[1]	Rank Acceptability Index														
		R1[2]	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
UNIMOD*	0.668	0.528	0.064	0.200	0.209	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSII	0.591	0.335	0.293	0.255	0.092	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSIII	0.416	0.132	0.289	0.179	0.400	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LOCREC*	0.256	0.005	0.047	0.066	0.004	0.703	0.157	0.016	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DIVRSI	0.336	0.000	0.308	0.300	0.270	0.094	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
HGMAIN*	0.165	0.000	0.000	0.000	0.000	0.161	0.252	0.557	0.009	0.021	0.000	0.000	0.000	0.000	0.000	0.000
YNGREN	0.155	0.000	0.000	0.000	0.026	0.015	0.548	0.226	0.141	0.029	0.009	0.001	0.002	0.004	0.000	0.000
DSMREF	0.127	0.000	0.000	0.000	0.000	0.000	0.016	0.170	0.757	0.010	0.047	0.000	0.000	0.000	0.000	0.000
PRVREN	0.107	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.699	0.164	0.086	0.012	0.008	0.000	0.000
LOWINV*	0.091	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.042	0.161	0.201	0.104	0.077	0.318	0.092	0.003
EXPREN*	0.087	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.017	0.011	0.351	0.053	0.047	0.111	0.380	0.000
MNIGRD	0.085	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.086	0.424	0.169	0.237	0.084	0.000
STDALN	0.085	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.221	0.655	0.090	0.005	0.000
LOWRUN*	0.080	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.114	0.111	0.039	0.185	0.373	0.111
DIVPES*	0.067	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.067	0.887

1. Holistic Acceptability Index - Centroid meta-weights (Section 3.9.2.5)
2. Rank
* "New" alternative – Expanded alternatives

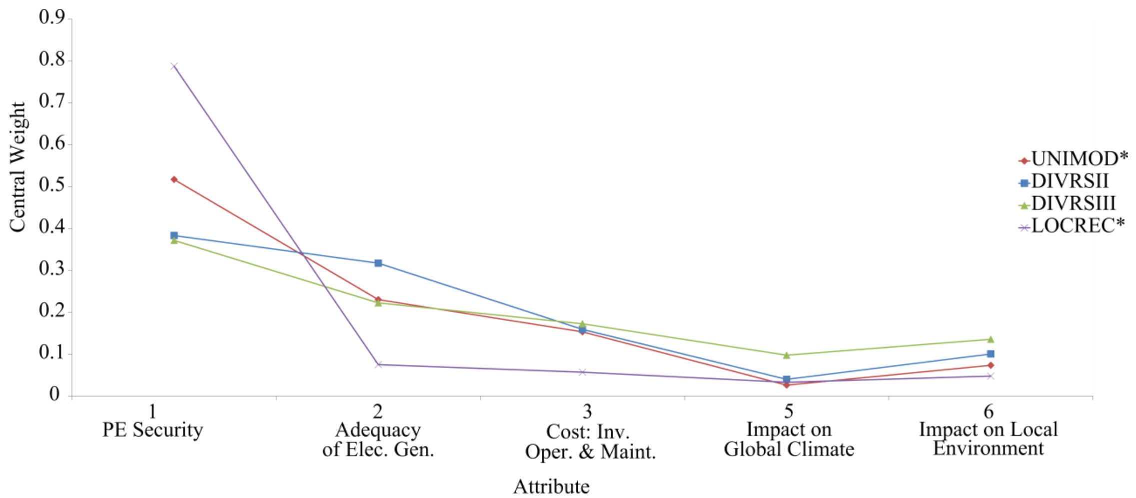


Figure D- 17 - Central weight vectors – Dev-C objective set - Exp. alt.: Case study ("New" alternatives are distinguished by " * ")

D.6.2 -VIP Analysis: Expanded alternatives

The values corresponding to Figure 6-19 are presented in Table D- 12. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 12 - Range of values – ECOWAS+ objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
UNIMOD*	0.699	0.984	0.040	
DIVRSI	0.695	0.936	0.193	
DIVRSII	0.695	0.936	0.193	
LOCREC*	0.568	1.000	0.239	
PRVREN	0.555	0.793	0.414	YES
YNGREN	0.529	0.958	0.315	YES
DSMREF	0.489	0.745	0.511	YES
HGMAIN*	0.487	0.826	0.513	YES
DIVRSIII	0.448	0.895	0.552	YES
EXPREN*	0.408	0.833	0.435	YES
MNIGRD	0.343	0.674	0.657	YES (Abs)
STDALN	0.306	0.686	0.694	YES (Abs)
DIVPES*	0.218	0.609	0.782	YES (Abs)
LOWINV*	0.059	0.728	0.941	YES
LOWRUN*	0.000	0.672	1.000	YES (Abs)

* “New” alternative – Expanded alternatives

The values corresponding to Figure 6-21 are presented in Table D- 13. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 13 - Range of values – ECOWAS objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
DIVRSI	0.705	0.936	0.193	
DIVRSII	0.705	0.936	0.193	
UNIMOD*	0.676	0.984	0.041	
LOCREC*	0.622	1.000	0.165	
YNGREN	0.564	0.958	0.282	YES
PRVREN	0.535	0.793	0.414	YES
EXPREN*	0.499	0.833	0.380	YES
DSMREF	0.489	0.745	0.511	YES
HGMAIN*	0.487	0.792	0.513	YES
DIVRSIII	0.448	0.895	0.552	YES
MNIGRD	0.343	0.672	0.657	YES (Abs)
STDALN	0.306	0.653	0.694	YES (Abs)
DIVPES*	0.218	0.609	0.782	YES (Abs)
LOWINV*	0.059	0.717	0.941	YES
LOWRUN*	0.000	0.653	1.000	YES (Abs)

* “New” alternative – Expanded alternatives

The values corresponding to Figure 6-22 are presented in Table D- 14. The values are shown for the full set of alternatives (e.g. dominated and non-dominated alternatives).

Table D- 14 – Range of values – Dev-C objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value	Maximum regret	Dominated
UNIMOD*	0.794	0.968	0.060	
DIVRSI	0.770	0.904	0.193	
DIVRSII	0.770	0.903	0.193	YES
DIVRSIII	0.740	0.895	0.105	YES
LOCREC*	0.575	1.000	0.220	
DSMREF	0.489	0.638	0.511	YES (Abs)
HGMAIN*	0.487	0.709	0.513	YES (Abs)
PRVREN	0.472	0.586	0.414	YES (Abs)
YNGREN	0.418	0.916	0.376	YES
MNIGRD	0.343	0.511	0.657	YES (Abs)
EXPREN*	0.333	0.666	0.571	YES (Abs)
STDALN	0.306	0.511	0.694	YES (Abs)
DIVPES*	0.218	0.341	0.782	YES (Abs)
LOWINV*	0.059	0.623	0.941	YES (Abs)
LOWRUN*	0.000	0.538	1.000	YES (Abs)

* "New" alternative – Expanded alternatives

D.7 -Sensitivity Analysis - Variation of performances

D.7.1 - Variation of performances

For attribute 6, evaluating the impact on global climate [Mton CO_{2eq} emissions], the calculated uncertainty of the evaluated performance of the alternative is used to find the min and max following the procedure detailed in the IPCC (2000). The min and max values for each of the alternatives calculated with this uncertainty are detailed in Table D- 15.

Table D- 15 – Variation of performances –Attribute 6. Impact on global climate

Alternative	Impact on Global Climate [Mton CO_{2eq} emissions]	
	Minimum value	Maximum value
PRVREN	213.4	340.7
YNGREN	225.6	332.4
MNIGRD	242.1	353.3
STDALN	232.4	341.8
DSMREF	229.2	336.8
DIVRSI	225.9	331.3
DIVRSII	224.8	329.6
DIVRSIII	216.7	320.6
UNIMOD*	229.8	338.2
DIVPES*	231.5	336.7
LOWINV*	249.9	366.2
LOWRUN*	220.3	325.5
LOCREC*	219.9	322.9
HGMAIN*	226.4	333.8
EXPREN*	236.2	343.3

* "New" alternative – Expanded alternatives
Calculations

D.7.2 -SMAA-2 Analysis: Sensitivity Analysis

The values corresponding to Figure 6-23 are presented in Table D- 16.

Table D- 16 - Rank acceptabilities - ECOWAS+ objective set - Performance variations (Perf. var.): Case study

Alt.	Holistic Acc. Index[1]	Rank Acceptability Index R1[2]	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
LOWINV*	0.301	0.131	0.097	0.083	0.078	0.073	0.074	0.069	0.064	0.062	0.061	0.054	0.060	0.045	0.036	0.015
HGMAIN*	0.291	0.119	0.095	0.083	0.084	0.077	0.071	0.072	0.066	0.067	0.066	0.057	0.054	0.046	0.034	0.012
LOWRUN*	0.287	0.116	0.100	0.086	0.071	0.070	0.068	0.068	0.066	0.062	0.064	0.061	0.056	0.055	0.040	0.017
DIVRSI	0.279	0.102	0.098	0.092	0.084	0.075	0.066	0.070	0.067	0.072	0.064	0.065	0.054	0.049	0.033	0.010
DIVRSII	0.276	0.103	0.091	0.086	0.080	0.079	0.079	0.073	0.072	0.070	0.064	0.062	0.055	0.047	0.032	0.008
UNIMOD*	0.270	0.099	0.087	0.081	0.078	0.080	0.080	0.078	0.071	0.066	0.066	0.063	0.056	0.050	0.033	0.012
DSMREF	0.251	0.084	0.078	0.082	0.078	0.074	0.077	0.072	0.072	0.070	0.065	0.066	0.065	0.053	0.049	0.015
STDALN	0.227	0.065	0.072	0.073	0.077	0.069	0.069	0.074	0.073	0.069	0.069	0.068	0.066	0.069	0.062	0.028
MNIGRD	0.214	0.057	0.067	0.069	0.064	0.072	0.063	0.071	0.072	0.072	0.073	0.073	0.070	0.076	0.071	0.032
PRVREN	0.194	0.041	0.056	0.061	0.071	0.068	0.072	0.070	0.075	0.073	0.071	0.073	0.081	0.076	0.077	0.038
LOCREC*	0.191	0.037	0.054	0.064	0.065	0.070	0.073	0.073	0.078	0.075	0.080	0.081	0.078	0.074	0.069	0.030
EXPREN*	0.158	0.017	0.039	0.050	0.058	0.064	0.065	0.065	0.070	0.072	0.075	0.074	0.083	0.099	0.109	0.061
DIVPES*	0.157	0.017	0.036	0.050	0.059	0.066	0.065	0.064	0.068	0.068	0.069	0.080	0.080	0.091	0.118	0.069
YNGREN	0.145	0.013	0.030	0.037	0.052	0.056	0.065	0.064	0.067	0.078	0.077	0.080	0.086	0.096	0.128	0.071
DIVRSIII	0.080	0.000	0.001	0.004	0.004	0.010	0.014	0.019	0.019	0.025	0.037	0.045	0.056	0.075	0.110	0.584

1. Holistic Acceptability Index - Centroid meta-weights (Section 3.9.2.5)
2. Rank
* "New" alternative – Expanded alternatives

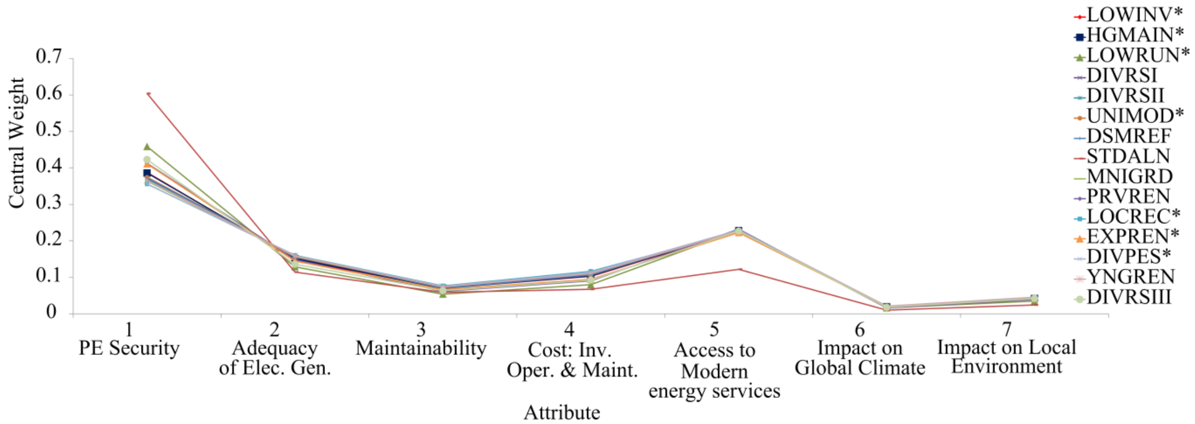


Figure D- 18 - Central weight vectors - ECOWAS+ objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

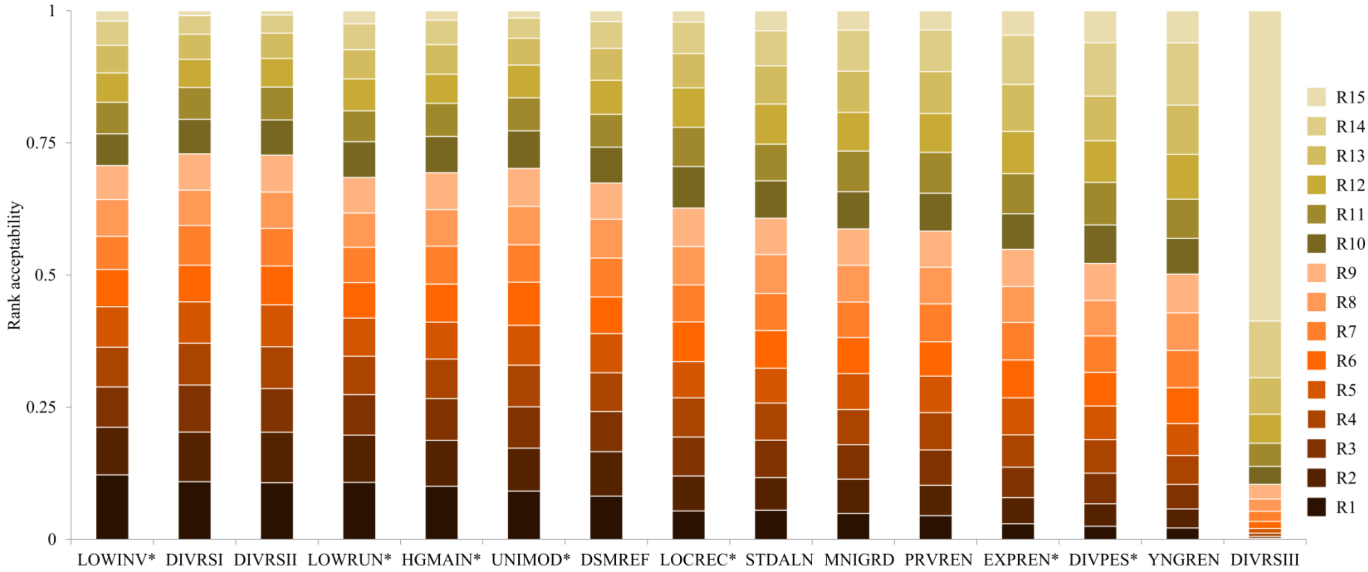


Figure D- 19 - Rank acceptability - ECOWAS objective set - Perf. var.: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

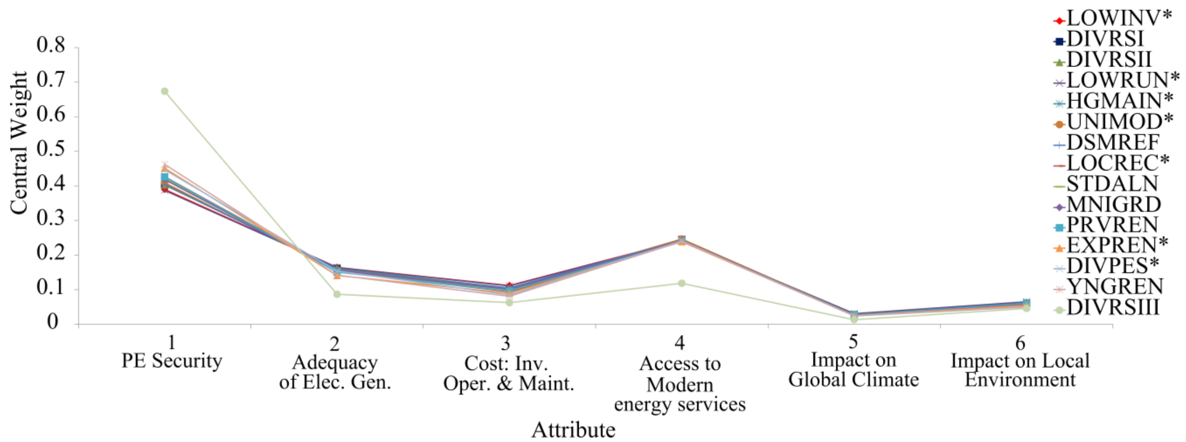


Figure D- 20 - Central weight vectors- - ECOWAS objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

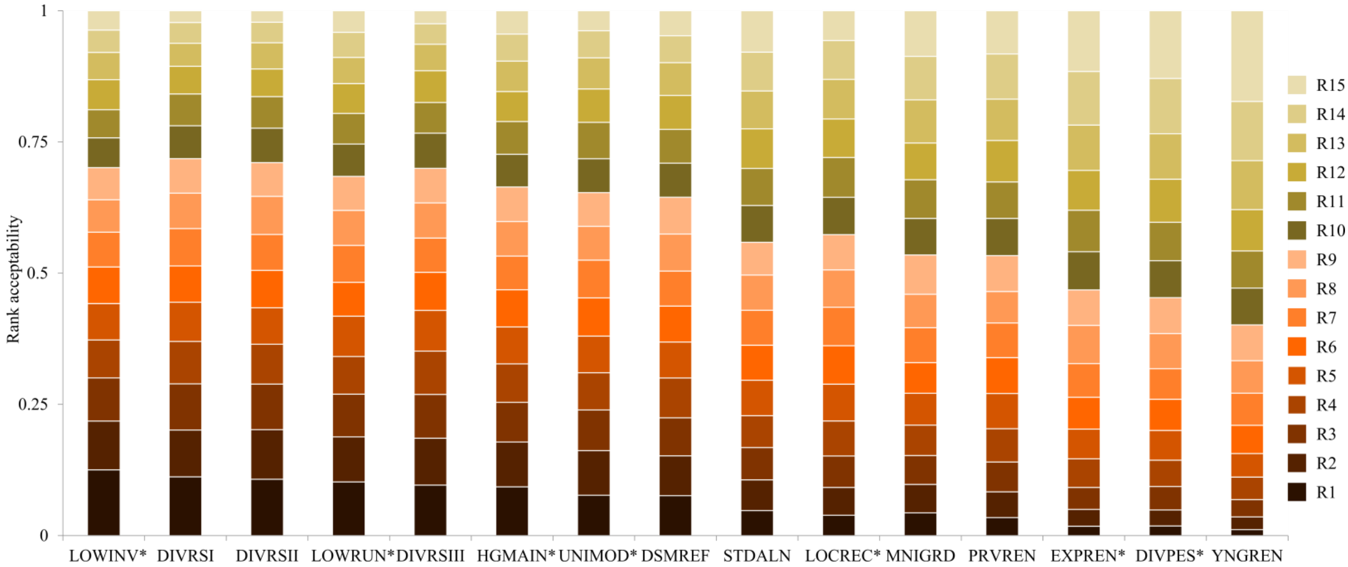


Figure D- 21 - Rank acceptability – Dev-C objective set - Perf. var.: Case study. (Alternatives are ranked in decreasing order of the holistic acceptability index and "New" alternatives are distinguished by " * ")

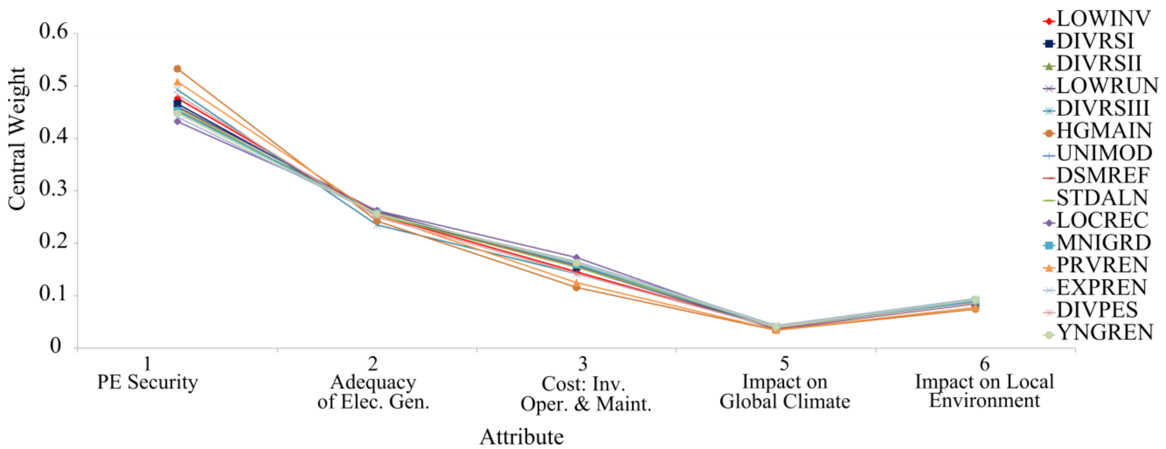


Figure D- 22 - Central weight vectors - Dev-C objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

D.7.3 -VIP Analysis: Sensitivity Analysis

The values corresponding to Figure 6-24 are presented in Table D- 17.

Due to the method used to carry out the sensitivity analysis in VIP Analysis (described in Section 6.5.2), the values in Table D- 17, Table D- 18 and Table D- 20 consist of minimum and maximum values of the range and not the maximum regret or information on the dominated alternatives.

Table D- 17 - Range of values – ECOWAS+ objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value
LOCREC*	0.093	1.000
UNIMOD*	0.090	1.000
YNGREN	0.085	0.999
DIVRSI	0.075	0.998
DIVRSII	0.075	0.998
EXPREN*	0.062	0.995
PRVREN	0.054	0.994
DSMREF	0.046	0.992
HGMAIN*	0.045	0.992
DIVRSIII	0.042	0.997
MNIGRD	0.032	0.990
STDALN	0.029	0.989
DIVPES*	0.020	0.988
LOWINV*	0.006	0.985
LOWRUN*	0.000	0.984

* “New” alternative – Expanded alternatives

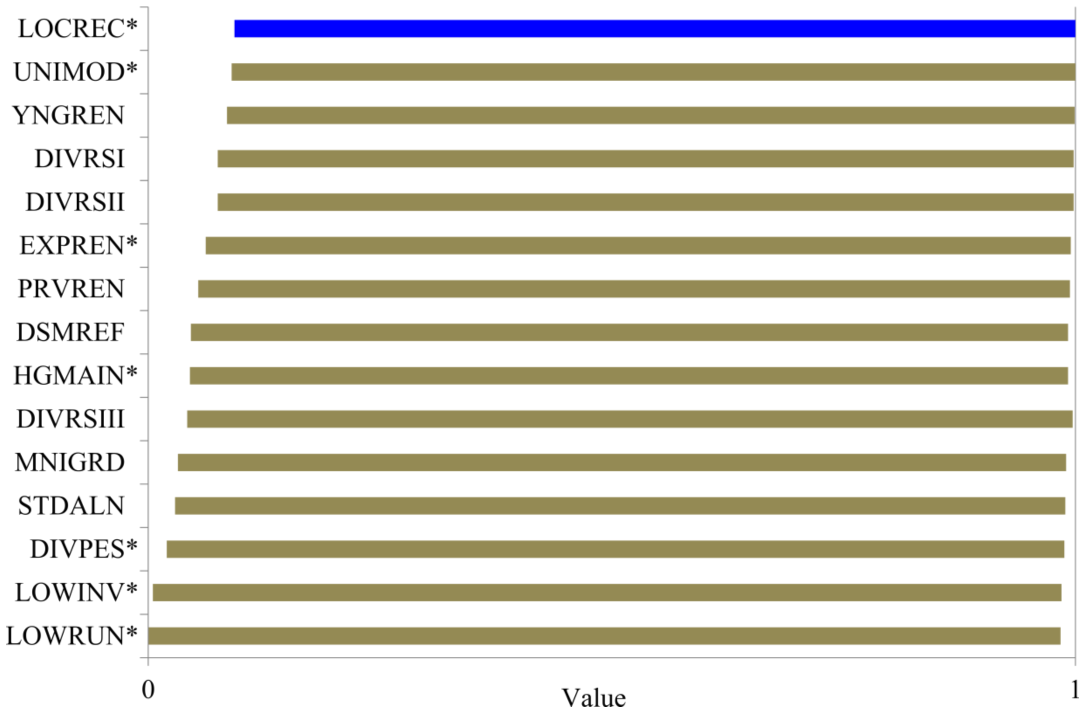


Figure D- 23 - Range of values - ECOWAS objective set - Perf. var.: Case study (“New” alternatives are distinguished by “ * ”)

The values corresponding to Figure D- 23 are presented in Table D- 18.

Table D- 18 - Range of values – ECOWAS objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value
LOCREC*	0.093	1.000
UNIMOD*	0.090	1.000
YNGREN	0.085	0.999
DIVRSI	0.075	0.998
DIVRSII	0.075	0.998
EXPREN*	0.062	0.995
PRVREN	0.054	0.994
DSMREF	0.046	0.992
HGMAIN*	0.045	0.992
DIVRSIII	0.042	0.997
MNIGRD	0.032	0.990
STDALN	0.029	0.989
DIVPES*	0.020	0.988
LOWINV*	0.005	0.985
LOWRUN*	0.000	0.984

* "New" alternative – Expanded alternatives

Table D- 19 - Ranking of Alternatives - ECOWAS objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

	Max Value ranking of alternatives w/ variations in performance		**Min Value** ranking of alternatives w/ variations in performance		**Max Regret** ranking of alternatives w/ variations in performance	
Most Attractive	UNIMOD*	1.000	LOCREC*	0.093	LOCREC*	0.907
	LOCREC*	1.000	UNIMOD*	0.090	UNIMOD*	0.910
↓	YNGREN	0.999	YNGREN	0.085	YNGREN	0.915
	DIVRSI	0.998	DIVRSI	0.075	DIVRSI	0.925
	DIVRSII	0.998	DIVRSII	0.075	DIVRSII	0.925
	DIVRSIII	0.997	EXPREN*	0.062	EXPREN*	0.938
	EXPREN*	0.995	PRVREN	0.054	PRVREN	0.945
	PRVREN	0.994	DSMREF	0.046	DSMREF	0.954
	HGMAIN*	0.992	HGMAIN*	0.045	HGMAIN*	0.955
	DSMREF	0.992	DIVRSIII	0.042	DIVRSIII	0.958
	MNIGRD	0.990	MNIGRD	0.032	MNIGRD	0.968
	STDALN	0.989	STDALN	0.029	STDALN	0.971
	DIVPES*	0.988	DIVPES*	0.020	DIVPES*	0.980
Least	LOWINV*	0.985	LOWINV*	0.005	LOWINV*	0.994
Attractive	LOWRUN*	0.984	LOWRUN*	0.000	LOWRUN*	1.000

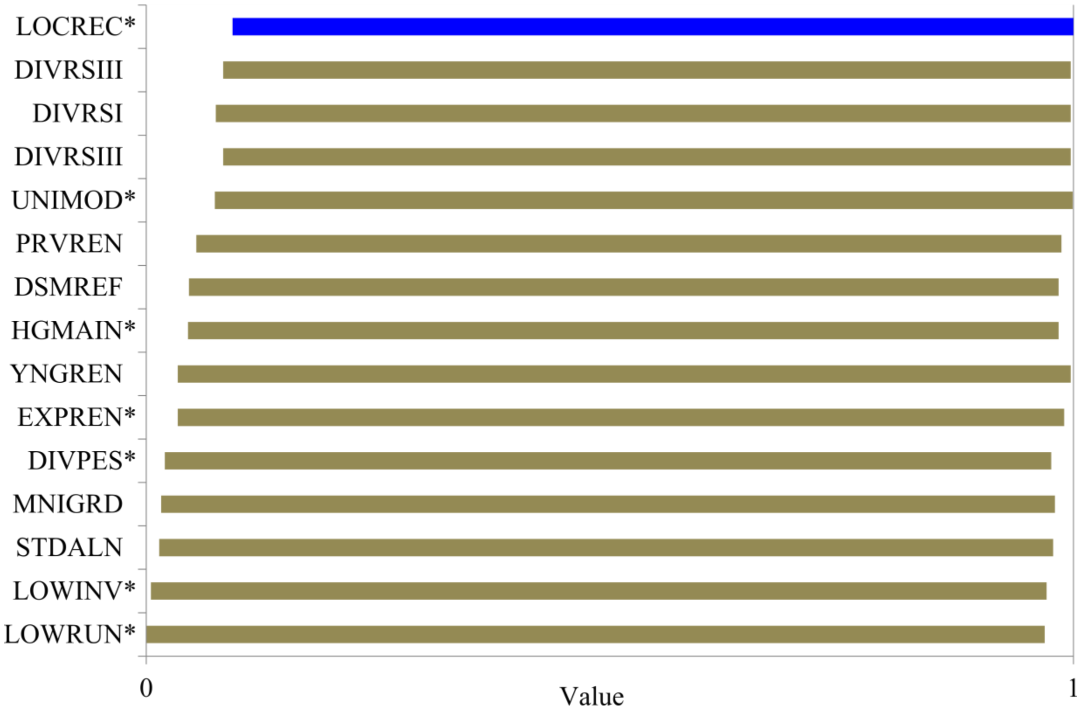


Figure D- 24 - Range of values - Dev-C objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

The values corresponding to Figure D- 24 are presented in Table D- 20.

Table D- 20 - Range of values – Dev-C objective set – Exp. alt.: Case study

Alternative	Minimum value	Maximum value
LOCREC*	0.093	1.000
DIVRSIII	0.083	0.997
DIVRSI	0.075	0.997
DIVRSIII	0.083	0.997
UNIMOD*	0.074	0.999
PRVREN	0.054	0.987
DSMREF	0.046	0.984
HGMAIN*	0.045	0.984
YNGREN	0.034	0.997
EXPREN*	0.034	0.990
DIVPES*	0.020	0.976
MNIGRD	0.016	0.980
STDALN	0.014	0.978
LOWINV*	0.005	0.971
LOWRUN*	0.000	0.969

* "New" alternative – Expanded alternatives

Table D- 21 - Ranking of Alternatives - Dev-C objective set - Perf. var.: Case study ("New" alternatives are distinguished by " * ")

	Max Value ranking of alternatives w/ variations in performance		**Min Value** ranking of alternatives w/ variations in performance		**Max Regret** ranking of alternatives w/ variations in performance	
Most Attractive	LOCREC*	1.000	LOCREC*	0.093	LOCREC*	0.907
	UNIMOD*	0.999	UNIMOD*	0.083	UNIMOD*	0.917
	DIVRSI	0.997	DIVRSI	0.075	DIVRSI	0.923
	DIVRSII	0.997	DIVRSII	0.075	DIVRSII	0.925
	DIVRSIII	0.997	DIVRSIII	0.074	DIVRSIII	0.925
	YNGREN	0.997	YNGREN	0.054	YNGREN	0.946
	EXPREN*	0.990	EXPREN*	0.046	EXPREN*	0.946
	PRVREN	0.987	PRVREN	0.045	PRVREN	0.954
	HGMAIN*	0.984	HGMAIN*	0.034	HGMAIN*	0.955
	DSMREF	0.984	DSMREF	0.034	DSMREF	0.963
	MNIGRD	0.980	MNIGRD	0.020	MNIGRD	0.980
	STDALN	0.978	STDALN	0.016	STDALN	0.981
	DIVPES*	0.976	DIVPES*	0.014	DIVPES*	0.983
	LOWINV*	0.971	LOWINV*	0.005	LOWINV*	0.994
Least Attractive	LOWRUN*	0.969	LOWRUN*	0.000	LOWRUN*	1.000

Appendix E

Energy planning document literature review

This annex contains the energy documents from the ECOWAS reviewed in Chapter 2.

The initial list of 51 EP documents identified in the main literature review of ECOWAS energy documents is presented below in Table E- 1.

The initial list of 41 EP documents identified in the supplementary literature review of ECOWAS energy documents is presented below in Table E- 3.

Table E- 1 – Initial list of energy documents identified in literature review

			Document type			
Country	Document name	Author	Energy Plan	Energy Policy	Energy Project or Program	Other*
Benin	Benin's electricity trade and generation needs for the period 2001 to 2020	(Bowen and Sparrow, 2001)				X
	Strategy for the Supply of Energy Necessary for the Achievement of the MDGs	**(MDEF and MEME, 2006)**	X			
Burkina Faso	Lettre de politique de développement du secteur de l'énergie	(MMCE, 2000)		X		
	La stratégie énergie domestique au Burkina Faso	(DGE - MMCE, 2005)		X		
	De l'électricité verte pour cent mille ruraux au Burkina Faso	(Fondation Energies pour le Monde and DGE, 2010)			X	
Cape Verde	**National energy plan**	**(MECC, 2004)**	X			
	Política energética de Cabo Verde	(MECC, 2008)		X		
	Renewable energy plan Cape Verde	**(DGE, 2011)**	X			
Gambia	National energy policy	(DoSPEMR, 2008)		X		
	Master plan for renewable energy based electricity generation in The Gambia	**(Flores, 2010)**	X			
Ghana	An energy roadmap for Ghana: From crisis to the fuel for 'economic freedom'	(USAID, 1999)				X
	Strategic national energy plan 2006-2020	(EC, 2006a)	X			
	Assessing policy options for increasing the use of renewable energy for sustainable development: Modelling energy scenarios for Ghana	(UN-ENERGY et al., 2006)	X			
	National energy policy	(MoE, 2009a)		X		
	Energy sector strategy and development plan	(MoE, 2010)		X		
	2011 energy (supply and demand) outlook for Ghana	(EC, 2011b)				X

Guiné-Bissau	Carta de política sectorial sobre o aprovisionamento das diferentes formas de energia	(MERN and SEE, 2010)	X			
Ivory Coast	L'Etude prospective du secteur forestier en Afrique	(MEF - Ivory Coast, 2001)				X
	Strategic development plan 2011-2030: Electricity and new and renewable energies	**(MMPE, 2011)**		X		
Liberia	Renewable energy and energy efficiency policy and action plan	(MLME, 2007)		X		
	Renewable energy and energy efficiency policy and action plan	(MLME, 2007)		X		
	National energy policy: An agenda for action and economic and social development	(MLME, 2009)		X		
	Simplified power system master plan - A primer for decision-making	**(NORAD and MLME, 2009)**	X			
	Liberia energy assistance program	(USAID, 2009)			X	
Mali	La politique énergétique de la République du Mali	(MMEE, 2005)		X		
	La politique énergétique nationale	(MMEE, 2006)		X		
Niger	Etude sur l'identifation des besoins en formation en énergie domestique	(CILSS and CNCEDAN, 2002)				X
	Stratégie nationale et plan d'actions sur les énergies renouvelables	(CNEDD et al., 2003)		X		
	Declaration de politique énergétique	(MME, 2004a)		X		
	Projet de création d'une société de traitement et de commercialisation du charbon minéral a des fins domestiques	(MME, 2004b)			X	
	La stratégie énergie domestique du Niger: Concept et opérationnalisation	(Bachir, 2005)		X		
	Improving Economic and Social Impact of Rural Electrification (IMPROVES-RE): Ateliers de restitution des plans locaux d'électrification	(IMPROVES-RE, 2006)			X	
Nigeria	National energy policy	(FRN and ECN, 2003)		X		
	Renewable energy master plan: Final draft report	(ECN and UNDP, 2005b)	X			
	Assessment of energy options and strategies for Nigeria: Energy demand supply and environmental analysis for sustainable energy development	**(ECN and IAEA, 2006)**	X			
	Renewable energy action plan	(FMPS and ICEED, 2006)			X	
	Strategies for regional integration of electricity supply in West Africa	(Gnansounou et al., 2007)				X
	Electricity demand forecasting in Nigeria using time series model	**(Mati et al., 2009)**	X			
Senegal	Planification intégrée énergie-environnement application du modèle LEAP au Sénégal	(Diallo et al., 1992)				X
	Energy and environment scenarios for Senegal	(Lazarus et al., 1993)				X
	Economics of greenhouse gas emissions	**(UNEP Risø and MENP, 2001)**	X			
	Lettre de politique de développement du secteur de l'énergie	(MEF and MMEH, 2003)		X		
	Development and climate, Country study: Senegal	(Sokona et al., 2003)				X
	Stratégie nationale de développement des énergies renouvelables pour la lutte contre la	(GoS, 2005)		X		

	pauvreté: Stratégie et Plan d'actions pour la relance du développement des énergies renouvelables				
	Préparation du plan énergie domestique du Sénégal	(Dia et al., 2008)			X
Sierra Leone	The energy policy for Sierra Leone (draft)	(MEP and CEMMATS, 2004)		X	
	The Sierra Leone energy sector: prospects & challenges	**(MEP, 2006)**	X		
Togo	Système d'information energétique – Togo	(MMEE, 2007)			X
	Support program for the control of traditional energies and the promotion of renewable energies in Togo	**(MERF et al., 2008)**	X		
	A model for a sustainable energy supply strategy for the social-economic development of Togo	(Ayenagbo et al., 2011)			
West Africa	L'énergie en Afrique a l'horizon 2050	(AFD and AfDB, 2009)		X	
WAPP	**Update of the Revised Master Plan for the Generation and Transmission of Electricity *Volumes 1-4: West African Electrical Energy Exchange System, West African Power Pool***	(ECOWAS, 2011)	X		

*Energy resource and/or access assessment OR Policy options report

Documents in **bold** were used in the current literature review.

The documents presented in Table E- 2 correspond to the documents and document codes presented in Chapter 2.

Table E- 2 - Original EP Means objectives and identified Fundamental objectives

Document	Fundamental Objectives [*Authors' addition, in absence of fundamental objective*]	Means Objectives	Comments
D1	Improvement of the comfort and the quality of life of inhabitants		
	[Increase economic development]	Growth of national economic competitiveness	
	Security of supply (of energy)		
	Environmental preservation		
D2	*[Increase economic development]*	Stimulate economic development by ensuring that energy plays a catalytic role in Ghana's economic development	"Catalytic role" is not defined and difficult to quantify and control
	[Increase system reliability] [Increase access to modern energy]	Consolidate, improve and expand existing energy infrastructure	
	[Increase access to modern energy]	Increase access to modern energy services for poverty reduction in off-grid areas	
	[Increase security of energy supply]	Secure and increase future energy security by diversifying source of energy supply	
	[Increase security of energy supply]	Accelerate the development and utilization of renewable energy and energy efficiency technologies so as to achieve 10% penetration of national electricity and petroleum demand mix respectively by 2020	
	[Increase economic development]	Enhance private sector participation in energy infrastructure development and service delivery	
	[Minimize environmental impacts attributed to the energy sector]	Minimize environmental impacts of energy production, supply and utilization	Three means objectives can be identified here
	[Improve governance of the energy sector]	Strengthen institutional and human resource capacity and R&D in energy development	
	Improve governance of the energy sector		

	[Increase economic integration of West African States]	Sustain and promote commitment to energy integration as part of economic integration of West African States	
D3	*[Increase access to modern energy]*	Increase access to modern cooking services	
	[Increase access to modern energy]	Increase access to modern mechanical and electrical services to rural populations	
	[Increase reliability of energy]	Ensure reliable electrical supply to urban and peri-urban households	
D4	*[Minimize environmental impacts attributed to the energy sector]*	Provision of efficient energy	
	Provision of reliable energy		
	Provision of affordable energy		"affordable energy" is not explicit and hard to quantify and control
	[Minimize environmental impacts attributed to the energy sector]	Ensure that exploitation of energy is sustainable and environmentally sound	"sustainable" is not explicit and difficult to quantify and control
D5	*Unclear Objectives*	-	
D6	*[Minimize climate change impacts attributed to the energy sector]*	Greenhouse Gas Emissions Mitigation	
D7	*[Increase system reliability]*	Forecast Electricity Consumption	
D8	*[Increase system reliability]*	Identify electricity generation options required to meet immediate demand, consistent with future development scenarios	
D9	*[Minimize environmental impacts attributed to the energy sector]*	Curb deforestation through promotion of household use of renewable energy as a substitute to traditional energy sources	
	[Minimize environmental impacts attributed to the energy sector]	Control traditional energy demand with increased use of improved cookstoves	
	[Minimize environmental impacts attributed to the energy sector] [Minimize adverse health impacts attributed to the energy sector] [Increase Access to Modern Energy]	Popularize use of gas for cooking in urban areas	
	[Minimize environmental impacts attributed to the energy sector] [Increase Security of Energy Supply]	Develop and promote greater use of Renewable Energies	
	Improve institutional and regulatory management of energy sources and governance in the energy sector		
D10	Expand access to improved energy services (and improve energy supply reliability)		1 objective separated here into 2 (Expand access to improved energy services and improve energy supply reliability)
	Improve energy supply reliability		
	Improve energy sector governance and regulation		
	Reduce health and environmental costs associated with energy supply and use		Mix of 2 or possibly 3 fundamental objectives. [Minimize environmental impacts attributed to the energy sector] [Minimize adverse health effects attributed to the energy sector] or *environmental refers to both [decrease impact on climate change attributed to energy sector] & [decrease deforestation attributed to energy sector]*
	[Improve governance of the energy sector]	To enhance women's participation in energy policy planning formulation implementation and monitoring	
D11	*[Increase security of energy supply]*	Provide insights on the relative effectiveness and costs of generic policy options to increase the share of renewable sources in the primary energy mix	

D12	[Increase system reliability] [Improve ability to provide affordable energy]	Ensure in the medium and long term an optimal electricity supply, reliable and at an affordable cost to the population of the various Member States (WAPP objectives)	Both "ensure" & "optimal" are not explicit and difficult to quantify and control
D13	*[Minimize environmental impacts attributed to the energy sector] [Increase security of energy supply]*	articulate a national vision, targets and a roadmap for addressing key development challenges facing Nigeria through the accelerated development and exploitation of renewable energy	
	[Increase access to modern energy]	Expanding access to energy services and reducing poverty, especially in the rural areas	Mix of two objectives, where reducing poverty is also a fundamental objective, but not energy sector specific.
	Stimulating economic growth, employment and empowerment		
	[Improve quality of life of populations] [Decrease rural emigration]	Increasing the scope and quality of rural services, including, schools, health services, water supply, information, entertainment and stemming the migration to urban areas	"Scope" is not explicit and difficult to quantify and control. Combination of multiple objectives
	[Minimize environmental impacts attributed to the energy sector] [Minimize adverse health effects attributed to the energy sector]	Reducing environmental degradation and health risks, particularly to vulnerable groups such as women and children	
	[Minimize environmental impacts attributed to the energy sector] [Increase Security of Energy Supply]	Improving learning, capacity-building, research and development on various renewable energy technologies in the country	
	[Increase Security of Energy Supply]	Providing a road map for achieving a substantial share of the national energy supply mix through renewable energy, thereby facilitating the achievement of an optimal energy mix.	"optimal" is not explicit and difficult to quantify and control
D14	*[Minimize environmental impacts attributed to the energy sector] [Increase Security of Energy Supply]*	Increase the share of renewable sources in the primary energy mix	
D15	*[Minimize environmental impacts attributed to the energy sector]*	Promote energy efficiency	
	[Increase system reliability]	Provide abundant energy	This was 1 objective separated here into 3 (Produce Abundant Quality and Cheap Energy)
	[Increase system reliability]	Provide quality Energy	
	Provide cheap Energy		"cheap" here assumed to mean *affordable*
	[Increase economic development]	Develop a policy of conquering the market (Market of electrical energy exchanges on inter-country connections)	

Table E- 3 - Initial list of energy documents identified in the supplementary literature review

			Document type			
Country	Document name	Author	Energy Plan	Energy Policy	Energy Project or Program	Other*
Benin	Politique et stratégie énergétique du Benin	(DGE - MMEH, 2003)		X		
	Strategic development plan for the energy sector of Benin	**(DGE - MEE, 2009)**	X			
	Identification des potentialités et modalités d'exploitation des sources d'énergies renouvelables sur l'ensemble du territoire national	(MEE and UNDP, 2010)				X
Burkina Faso	La stratégie énergie domestique au Burkina Faso	(DGE - MMCE, 2005)				X
Cape Verde	**Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde**	**(Segurado et al., 2011)**	X			
	Development of energy projections: CLIMA-IMPACTO project (MAC/3/C159).	**(Factor CO2, 2012)**	X			
	O impacto das energias renováveis na economia dos países emergentes: o caso de Cabo Verde	(Monteiro, 2012)				X
	Renewable energy projects to electrify rural communities in Cape Verde	(Ranaboldo et al., 2014)			X	
	Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde	**(Segurado et al., 2015)**	X			
Gambia	Promoting renewable energy based mini grids for productive uses in rural areas of The Gambia	(UNIDO et al., 2011)			X	
	Electricity strategy and action plan	**(AF-MERCADOS EMI, 2012)**	X			
	The Gambia: Renewables readiness assessment	(IRENA, 2013b)				X
Ghana	Electrification planning using Network Planner tool: The case of Ghana	(Kemausuor et al., 2014)				X
Liberia	Draft Renewable Energy and Energy Efficiency Policy and Action Plan of Liberia	(MLME, 2007)		X		
	National energy policy: An agenda for action and economic and social development	(MLME, 2009)		X		
	Options for the Development of Liberia's Energy Sector	(World Bank, 2011b)	X			
Mali	Mali Energy Conservation Development Strategy	(AfDB, 2010a)			X	
	Stratégie de développement de la maitrise de l'énergie au Mali	(AfDB, 2010b)				X
Niger	Bilan énergétique et perspectives pour une politique énergétique ambitieuse au Niger	(CDC, 2009)				X
Nigeria	National Energy Policy	(FRN and ECN, 2003)		X		
	Draft National Energy Masterplan (NEMP)	(ECN and FMST, 2014b)	X			
	An energy system planning model for the industrial sector in Nigeria	**(Njoku, 2008)**	X			
	More for less: How decentralised energy can deliver cleaner, cheaper and more efficient energy in Nigeria	**(WADE et al., 2009)**	X			
	Power generation scenarios for Nigeria: An environmental and cost assessment	(Gujba et al., 2011)				X

	Low-carbon Africa: Nigeria	(ICEED and Christian Aid, 2011)			X	
	On energy for sustainable development in Nigeria	(Oyedepo, 2012)				X
	Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications	**(Aliyu et al., 2013)**	X			
	An integrated impact assessment of hydrogen as a future energy carrier in Nigeria's transportation, energy and power sectors	**(Amoo and Fagbenle, 2014)**	X			
	Draft National Renewable Energy & Energy Efficiency Policy (NREEEP)	(FMST and ECN, 2014)		X		
	Renewable energy masterplan: Revised draft	(ECN and FMST, 2014a)	X			
Senegal	Local and national electricity planning in Senegal: Scenarios and policies	(Sanoh et al., 2012)				X
	Modeling the transition towards a sustainable energy production in developing nations	**(Thiam et al., 2012)**	X			
	Evaluation rapide et analyse sommaire des ecarts en matière d'accès aux services énergétiques (ASE) des populations du Sénégal	(UNDP, 2012)				X
Sierra Leone	National energy policy for Sierra Leone	(Government of Sierra Leone and MEP, 2012)		X		
Togo	A model for a sustainable energy supply strategy for the social-economic development of Togo	(Ayenagbo et al., 2011)				X
	Evaluation rapide et analyse des Gaps	(SE4ALL, 2012)				X
ECOWAS	Energy for sustainable development: policy options for Africa	(UN-ENERGY/Africa, 2007)				X
	Energy access scenarios to 2030 for the power sector in sub-Saharan Africa	**(Bazilian et al., 2012)**	X			
	ECOWAS renewable energy policy (EREP)	(ECREEE, 2012a)		X		
	ECOWAS Energy Efficiency Policy (EEEP)	(ECREEE, 2012b)		X		
WAPP	**West African Power Pool: Planning and Prospects for Renewable Energy**	(IRENA, 2013a)	X			

*Energy resource and/or access assessment OR Policy options report

Documents in **bold** were used in the current literature review.